A STUDY OF THE FLUCTUATIONS OF THE WIND FIELD OVER THE TROPICAL INDIAN OCEAN

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Monterey, California

THESIS

A STUDY OF THE FLUCTUATIONS OF THE WIND FIELD OVER THE TROPICAL INDIAN OCEAN

by

Gary Ward Bryant

March 1975

Thesis Advisor: C.-P. Chang

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In general, the results of the power spectra computed show a seven-day peak which seems most significant. A four-

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five day peak and a thirteen-day peak were also found at some stations. The cross-spectrum analysis shows little correlation of the peaks, indicating uncertainty in the significance of the spectral results.

The results of the time cross-section analysis, done over two one-month periods, indicate a possible fluctuation time scale of 10-20 days at most stations; and in many cases, the fluctuations appear to propagate downward.

Due to the low density of available stations and the poor quality of the data, the results are considered very tentative. Further study is suggested, but only after the quality of the data can be improved.

A Study of the Fluctuations of the Wind Field
Over the Tropical Indian Ocean

by

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requirements for the degree of

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Using radiosonde data from six widely scattered stations in the Indian Ocean, an attempt was made to identify quasi-periodic wind oscillations during the 1973-1974 winter monsoon season. The data were analyzed using spectrum analysis and time cross-section analysis techniques.

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Due to the low density of available stations and the poor quality of the data, the results are considered very tentative. Further study is suggested, but only after the quality of the data can be improved.

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I. INTRODUCTION

Synoptic-scale tropical wave disturbances have been studied observationally with various techniques. Ordinary map analysis has been used in case studies of individual systems by Riehl (1945, 1967), Palmer (1952), Yanai (1961, 1963), and others. Such case-study approaches have been highly successful when the data network was adequate. Unfortunately, the tropical regions in general suffer from a very low density of reporting stations. In such cases, a composite approach has been found to be more successful than the standard synoptic techniques. Reed and Recker (1971) and Williams and Gray (1973) used such an approach and found it to be extremely useful in describing the average properties of the disturbances.

A convenient alternative to the compositing approach is the spectrum analysis, which is an entirely objective technique. It is important to note that most studies using a spectrum analysis approach have been of a heuristic or diagnostic nature, rather than purely statistical (Julien, 1972). Thus, most prior spectrum analysis studies have had more in common with the case-study and compositing approaches than a purely statistical spectrum analysis.

The early synoptic studies (Riehl, 1945) showed the existence of easterly waves in the Caribbean Ocean. Similar waves were also found in the tropical Northwest

Pacific region by Riehl (1948) and Hubert (1949). These waves were found to have a period of three-four days and a wavelength of 1,500-2,000 kilometers.

Most recent studies in the tropical Pacific Ocean have used the spectrum analysis approach, and two groups have made significant contributions in this area. One group was Yanai and his collaborators at Tokyo University, who used data from mostly the central Pacific stations. The second group was Wallace and his collaborators at the University of Washington, who used mainly the Western Pacific stations. Both groups consistently found a wave period of four-five days, suggesting that the waves may be similar to the easterly waves studied earlier.

In addition to the four-five day periodicity, Wallace and Chang (1969) also found a ten-fifteen day fluctuation in the zonal component wavelength on the order of 10,000 kilometers.

Spectrum analysis has also been used in other areas. Burpee (1972, 1974) did extensive work in the northwestern part of Africa during the Northern Hemisphere summer. A dominant fluctuation of four-five day periodicity with a horizontal wavelength of 2,000-4,000 kilometers was found.

Some observational studies near the Indian Ocean have been made but their results generally appear to be quite inconclusive. Rao and Murty (1973), in a spectrum analysis study using data from Singapore, Byan Lepas and Saigon, found an indication of four-five day fluctuations. However,

a lack of vertical correlation in this period band casts some doubts to the significance of these fluctuations. Another spectral study by Subbaramayya and Rao (1974), over the Indian continent, found periods of eight days and three-four days above 200 mb in both components of the wind, and a period of ten-twelve days at the levels between 900 mb and 500 mb. Malay (1974) did a similar study for five Indian Ocean stations and found periodicities of seven days and fifteen days at several levels.

Due to the relatively small number of studies undertaken and the increased interest in the Indian Ocean, the purpose of this study is to perform a spectral and time cross-section analysis of some newly available radiosonde data in an attempt to diagnose the disturbances in this region.

II. DATA

The study was initially planned to include all available tropical Indian Ocean stations. Radiosonde data for nine stations were acquired from the National Weather Records Center in Ashville. After an examination of the original data, it was found only six stations, shown in Figure 1, may be considered to have reasonably sufficient number of reports to warrant a study. The data covered the time period from October 1, 1973 to April 30, 1974, which corresponds to the winter monsoon season. These are twice-daily reports, which give a total of 424 data points for the entire period.

Due to the many gaps in the data, only five mandatory levels from 850 mb to 300 mb were used in this study. In addition, only the wind data were found complete enough to render the analysis meaningful.

All the selected six stations were used in two one-month time cross-section analysis. However, only four of them have sufficiently complete data for the seven-month period to warrant spectral analysis.

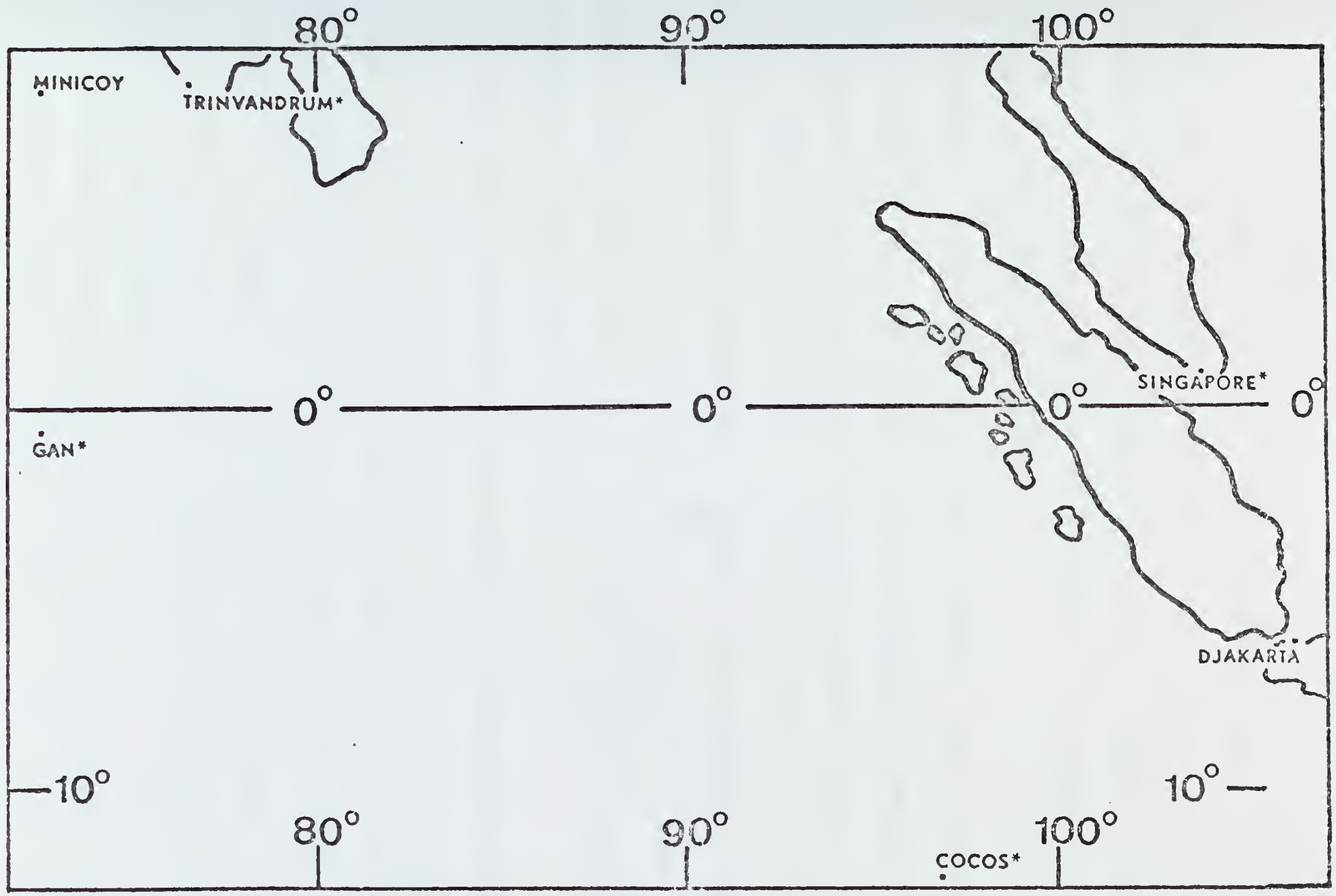


Figure 1. Radiosonde stations used in this study. Asterisk (*) indicates those used in spectral analysis.

III. SPECTRAL ANALYSIS AND RESULTS

A. POWER SPECTRUM

The original wind data were placed in zonal (u) and meridional (v) components, and the missing data were linearly interpolated. Since in several cases as many as eight-ten data points were missing in sequence, some adverse effect was expected.

Before calculating the power spectra, the computed u and v component time series were filtered to remove the effects of fluctuations with periods greater than 25 days. The filter used was a 98-point high pass Gaussian filter designed by Holloway (1958). The standard deviation of this filter is 8.33. The filter reduces the number of data points from 424 to 326. The theoretical response function of the filter is shown in Figure 2.

The power spectra and cross spectra were computed at the W.R. Church Computer Center of the Naval Postgraduate School. The program used was the BMD02T of the UCLA Biomedical Statistical Program Package. Fifty lags were used which correspond to a lag period of 25 days. Spectral information for the program was given in intervals of 0.02 cycles per day (cpd).

The power spectra were tested for statistical significance after Mitchell, et al., (1966). Since persistence is present in nearly all series, it has been found that

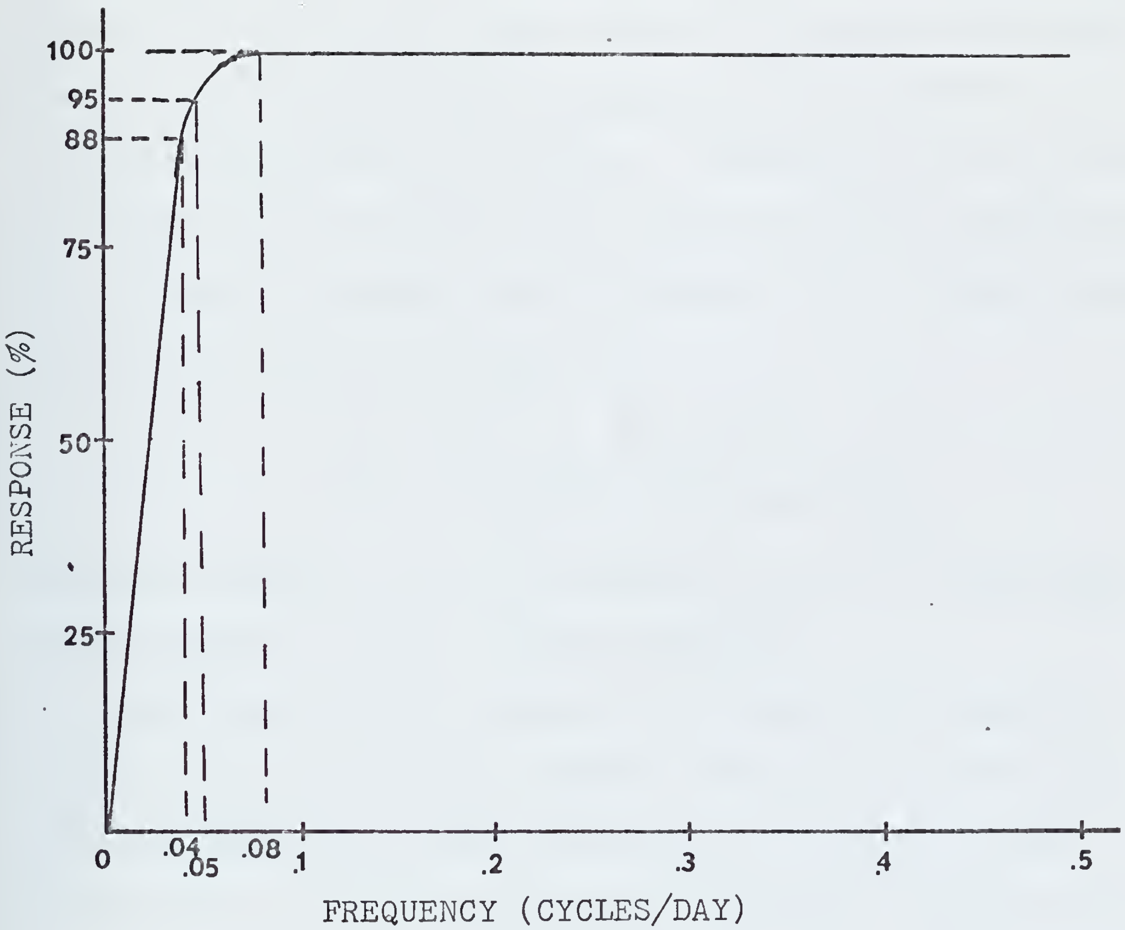


Figure 2.

Theoretical response function for 98-point Gaussian filter with σ = 8.33 and $R(f)=1 - \exp(-2\pi^2 \sigma^2 f^2)$, f is frequency.

the choice of a Markov "red noise" continuum as the "null" continuum is reasonable. Each time series in this analysis was first tested to determine if it fits the null continuum or not. This was done by comparing the lag-one serial correlation coefficient (r_1) with that of the first one (r_2) or two (r_3) lags greater than r_1 to see if the exponential relation, $r_2 = r_1^2$ and $r_3 = r_1^3$ is satisfied. After determining that the series does fit the Markov red-noise continuum, the null continuum may be constructed by the following approximate procedure. Assuming r_1 is an unbiased estimate of the population lag-one correlation coefficient, the following equation may be evaluated for various harmonic numbers k, between k=0 and k=m:

$$S_k = \bar{s} \left[\frac{1 - r_1^{\,2}}{1 + r_1^2 - 2r_1 \cos \pi k/m} \right]$$

In this equation, $\bar{s}$ is the average of all m + 1 raw spectral estimates in the computed spectrum.

After constructing the null continuum and comparing it to the spectrum being studied, deviations of the spectral estimates were then tested on an "a priori" basis to determine if they possess any statistical significance. The statistic associated with each spectral estimate is the ratio of the magnitude of the spectral estimate to the local magnitude of the continuum. Tukey (1950) found this to be distributed as the 'chi' squared (χ^2) divided by degrees of freedom (DOF), where

$$\mathrm{DOF} = \frac{2N - m/2}{m} .$$

Here the values of N and m are the number of data points and lags, respectively. For this study, the χ^2 / DOF value for a one-tailed test of a 95% confidence level is 1.68.

B. RESULTS OF THE POWER SPECTRUM ANALYSIS

Although the spectral estimates were calculated for frequencies up to 1 cpd, only spectral values for frequency less than 0.26 cpd are shown, because they generally fall off rapidly toward higher frequencies.

The power spectral estimates for the u and v components were plotted and compared with the 95% confidence levels as shown in Figures 3 through 6. The confidence level is shown as the dashed line in the figures.

The power spectra for Trinvandrum are shown in Figure 3. For the u component, the 850-mb level (u_{850}) shows significant power in the frequency band of 0.08-0.15 cpd. The 700-mb level (u_{700}) exhibits significant power in the band of 0.05-0.10 cpd. At 500 mb, a single frequency 0.06 cpd is significant, and at 400 mb a peak occurs at 0.09 cpd. Significant peaks are detected in the 0.08-0.10 cpd band and the 0.17-0.21 cpd band at 300 mb.

The v-component spectra shows significant power at the 850-mb level (v_{850}) in the frequency bands of 0.06-0.11 cpd and 0.12-0.16 cpd. The v_{700} spectrum is significant only in the frequency of 0.14 cpd. Neither v_{500} nor v_{400} has any significant peaks. In the v_{300} spectrum,

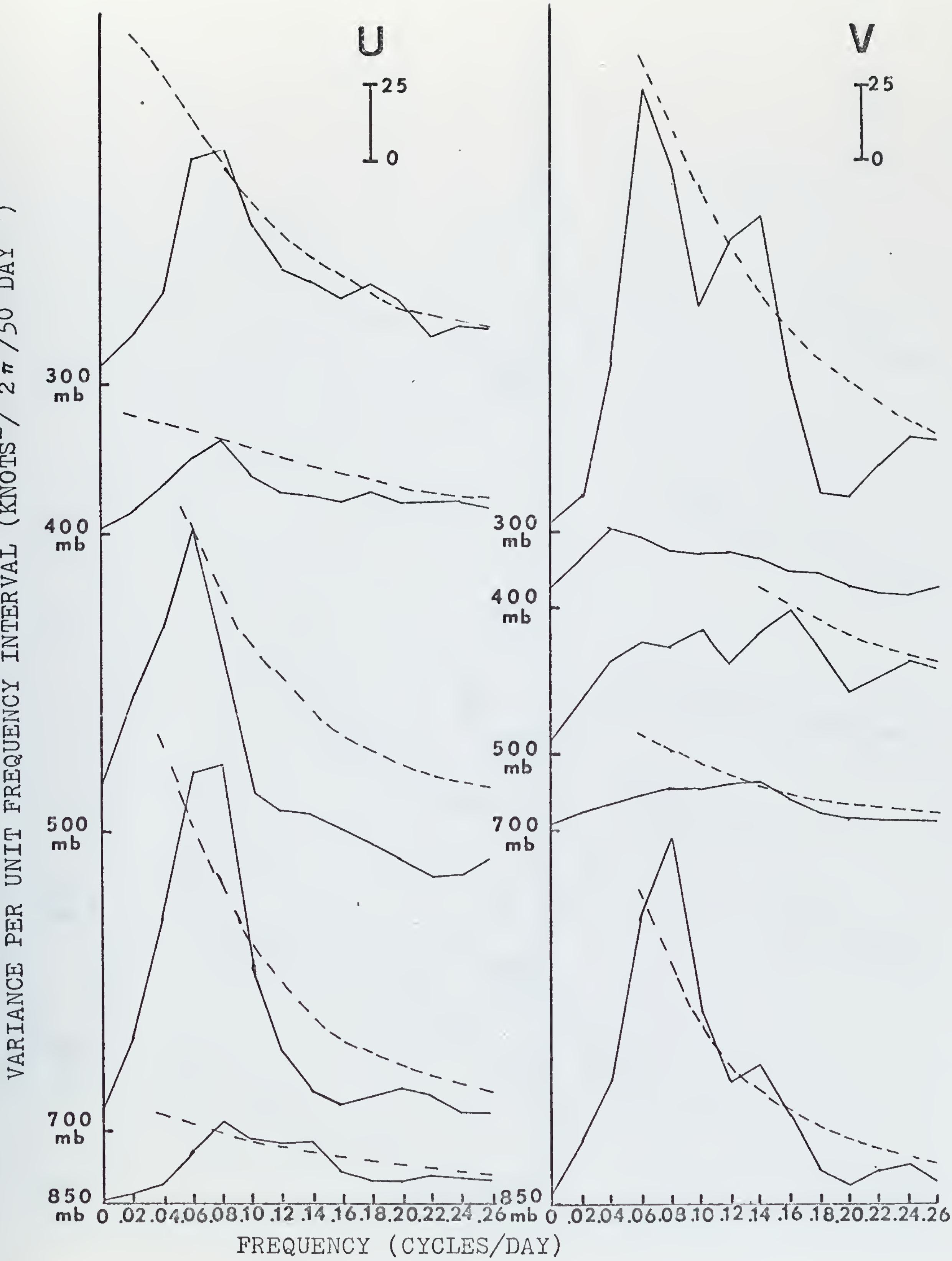


Figure 3. Power spectra for u and v components at Trinvandrum. Dashed line represents 95% confidence level for each series, not shown for v_{400}.

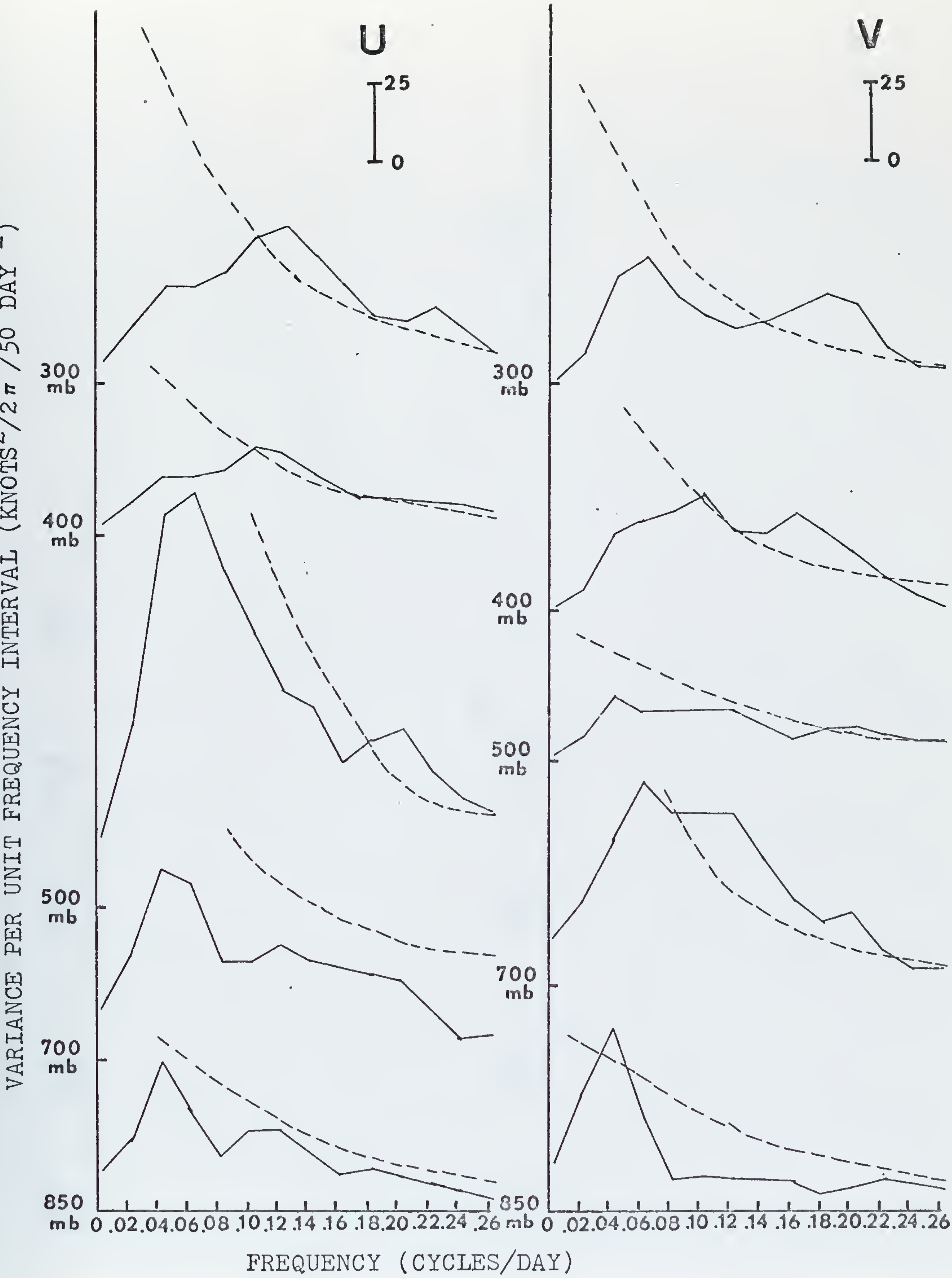


Figure 4. Power spectra for u and v components at Gan. Dashed line represents 95% confidence level for each series.

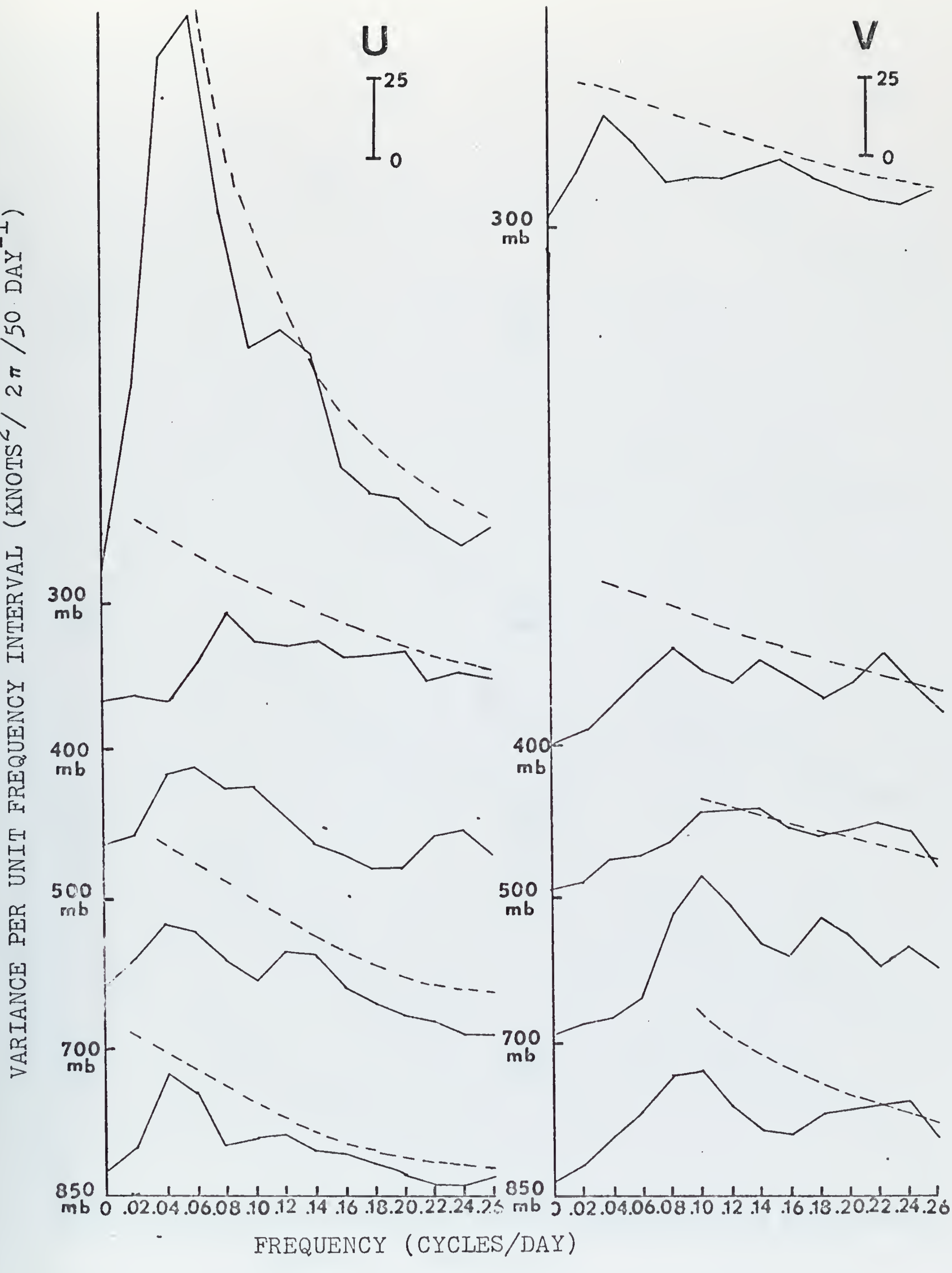


Figure 5. Power spectra for u and v components at Singapore. Dashed line is 95% confidence level for each series, not shown for u_{500} or v_{400}.

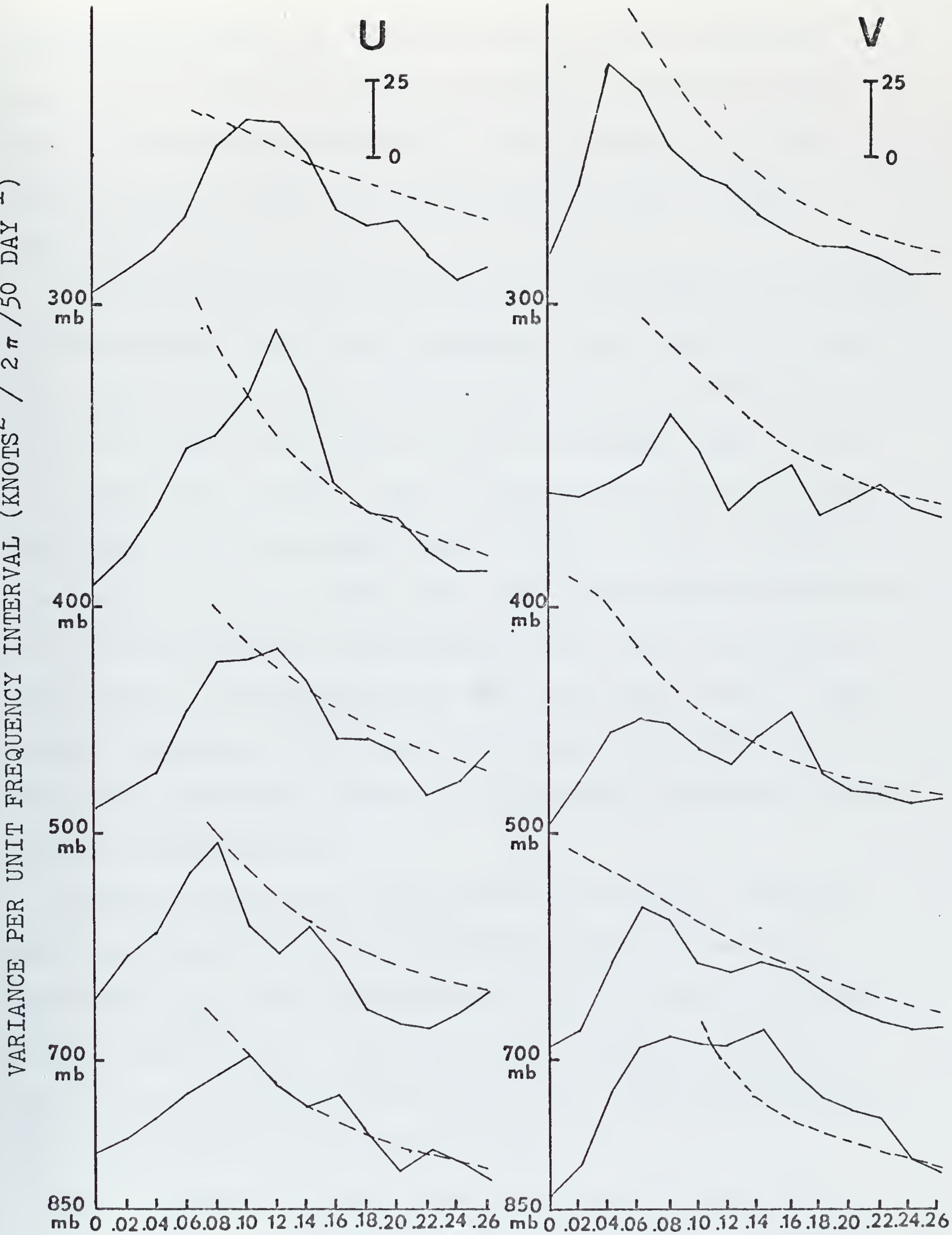


Figure 6. Power spectra for u and v components at Cocos Island. Dashed line represents 95% confidence level.

a significant band was found in the 0.12-0.16 cpd band. Over all, the band centered at 0.08 cpd (period 13 days) seems to be most significant at this station due to the large amount of power in u_{500}, v_{700} and some in u_{700} and u_{300}.

Subbaramayya and Rao (1974) have calculated wind spectra at Trinvandrum. For the u component, they found the spectral peaks at eight days (0.125 cpd) and three-four days (0.25-0.33 cpd) above 500 mb and ten-thirteen days (0.08-0.10 cpd) below 500 mb. For v component, they found spectral peaks of seven-eight days (0.125-0.14 cpd) and three-four days (0.25-0.33 cpd) above 500 mb and seven-eight days (0.125-0.14 cpd) and ten-thirteen days (0.08-0.10 cpd) below 500 mb. Although these periodicity bands seem to fall in the vicinity of the present findings, they must be considered inconclusive because of the large variations between levels and parameters.

Figure 4 shows the u and v spectra at Gan. The u_{850} and u_{700} spectra have no significant peaks. The next spectrum, u_{500}, has a large peak in the 0.18-0.26 cpd band. At the 400-mb level, two significant frequency bands appear, 0.12-0.16 cpd and 0.20-0.26 cpd. The same bands are also significant at the 300-mb level.

The v component shows some significance at all five levels. The significant "peak" shows up in the frequency band of 0.03-0.06 cpd for v_{850} which is in the filter cutoff range and will not be considered. For v_{700}, the

significant frequency band is 0.08-0.24 cpd, and for v_{500} it is 0.20-0.25 cpd. The v_{400} spectrum is significant for the bands of 0.12-0.14 cpd and 0.15-0.22 cpd. At v_{300}, it is 0.16-0.24 cpd. Thus, there seem to be two common significant frequency bands occurring at Gan--one centered near 0.14 cpd (seven days) and the other near 0.16-0.24 cpd (four-five days). It is interesting to note that Malay (1974) has found a significant periodicity of seven days at this station for the previous year.

Singapore's power spectra, shown in Figure 5, have almost no significant power in u at all levels. On the other hand, the v spectra have significant peaks centered at 0.23 cpd at 850, 500, and 400-mb levels. The corresponding common periodicity is about four-five days.

Figure 6 shows the power spectra for Cocos Island. Substantial amount of power in u is seen between 0.08-0.16 cpd at the three upper levels, 300, 400, and 500 mb. The main v peak occurs in the 0.14-0.18 band at 500 and 850-mb levels, which is also reflected in u_{850}.

In summary, the significant frequencies seem to vary greatly from station to station and sometimes from level to level. Thus, no general conclusion can be drawn for the entire area, except to say that three period ranges centered at the following periods may be significant: thirteen days (or 0.08 cpd, for Trinvandrum), seven days (or 0.14 cpd for Trinvandrum, Gan and Cocos Island), and four-five days (for Gan and Cocos Island). Among them the seven day periodicity seems to be most significant.

C. CROSS-SPECTRUM ANALYSIS

Three cross-spectral analyses were performed. The first is the analysis that crosses all levels in the vertical at each station for each component. The series at 700 mb was always chosen as the base series. The purpose of this inter-level cross-spectrum analysis is to determine the vertical structure of the fluctuations.

The second cross-spectrum analysis crosses the u and v components at each level at the same station. The purpose of this analysis is to give an indication of the horizontal tilt of the wave, because the phase relationship between u and v depicts the pattern of streamlines.

The last type of cross-spectrum analysis performed in this study was an inter-station analysis. In this analysis, the component at one level and one station is crossed with the same component at the same level but a different station. The results of this type analysis may give an indication of the wavelength of the wave and the direction of propagation. Obviously, the distance between stations becomes an important factor in the inter-station analysis.

The coherence-squared values and the phase differences between two series were given by the cross-spectrum analysis. The coherency-squared values obtained were first tested for statistical significance utilizing the probability points of distribution compiled by Amos and Koopmans (1963). Prior to entering the tables, the DOF

were determined from the relationship,

$$DOF = 1.25\ N/M$$

The value of N is the number of data points (326) and M is the number of lags (50). The resultant DOF is 8.2 and the coherency-squared values for the 90% and 95% significant levels are 0.280 and 0.348, respectively. The phase relationships for the frequency bands with significant power spectrum peaks and significant coherency-squared values were then used to determine the structure of the fluctuations.

D. RESULTS OF CROSS-SPECTRA

Generally speaking, only a few cross-spectra were found that can be considered as satisfying the significance level. For the inter-level cross-spectra, the few significant coherency-squared values all give roughly an in-phase relationship between different levels. However, the frequencies at which these significant correlations occur scatter quite widely, and no conclusive results can be drawn from these results. The same is true for the inter-parameter and inter-station cross-spectra. Their values thus will not be presented. It is felt that these poor results may be due to the poor quality and especially the large gaps in the data.

IV. TIME CROSS-SECTION ANALYSIS

A. TIME CROSS-SECTION ANALYSIS

Since the spectral analysis provides no conclusive results, a time cross-section analysis was performed. The time cross-section analysis was done at all six stations shown in Figure 1.

Due to large gaps in the wind data, the entire seven-month period could not be used. Instead, two one-month periods, approximately representative of two monsoom transition seasons, were used for each station. At Trinvandrum, Minicoy and Gan, the time cross-section analysis was done using October 1973 and April 1974 data; while at Singapore, Djakarta and Cocos Island, the December 1973 and April 1974 data were used. The choice of month is based on the fewest number of missing data, although it is realized October and April are transition months. The u and v components were separately analyzed in all cases.

In this analysis, the average u and v for each cross-section were first calculated and are given in Figures 7-12. It is seen that most of the monthly averaged wind profiles are different from station to station. This may be indicative of the complex situation of the monsoon flow and may partly explain the different spectral characteristics at the different stations. These averaged u and v values were then subtracted from the original series at

Figure 7. Average u and v components at Trinvandrum for October 1973 and April 1974.

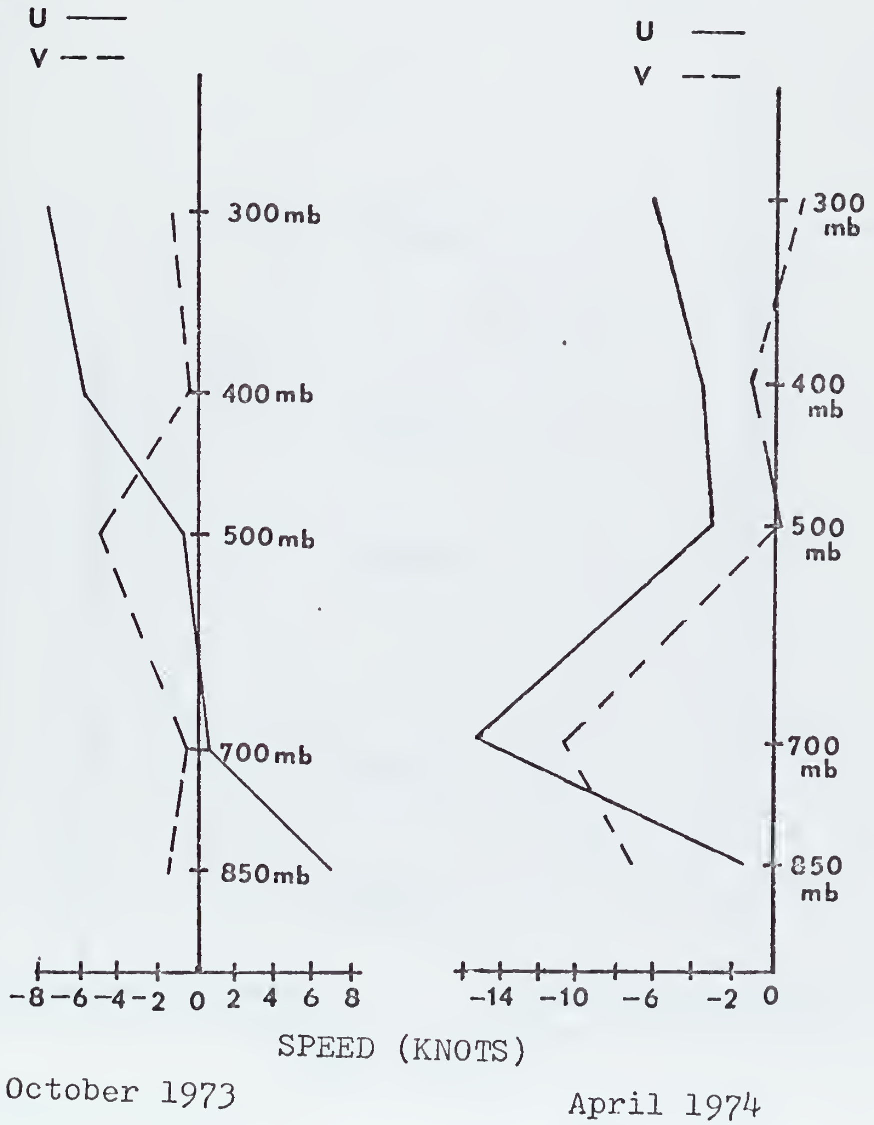


Figure 6. Same as Figure 7 except at Minicoy.

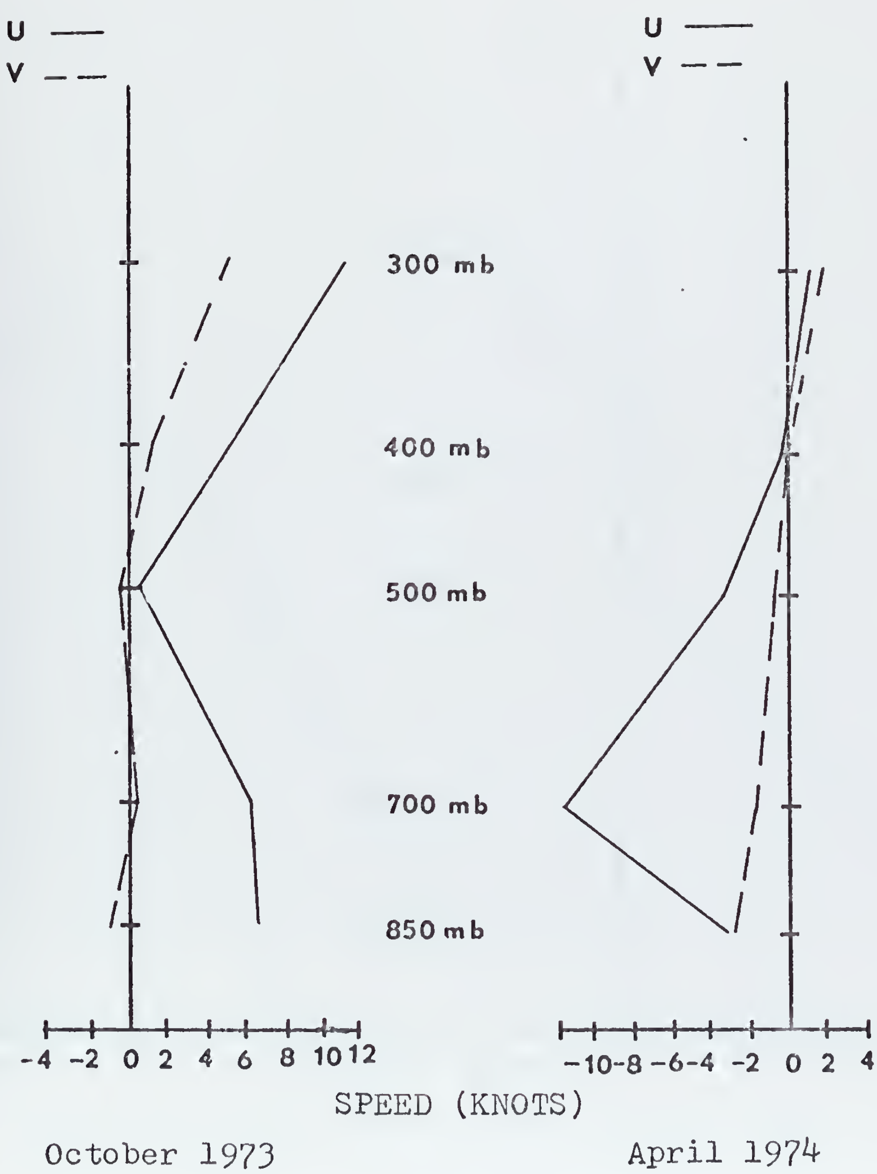


Figure 9. Same as Figure 7 except at Gan.

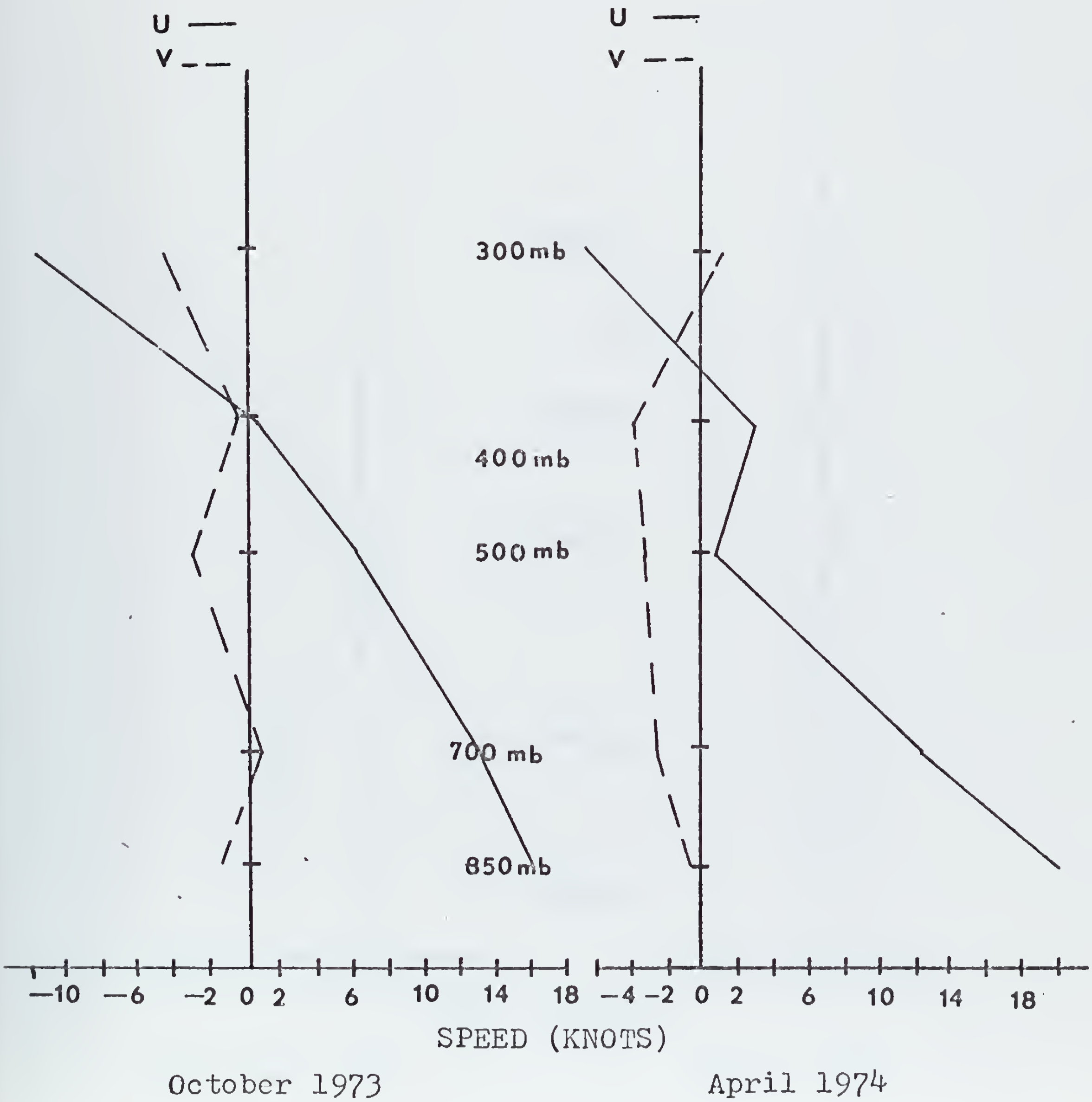


Figure 10. Average u and v components for December 1973 and April 1974 at Singapore.

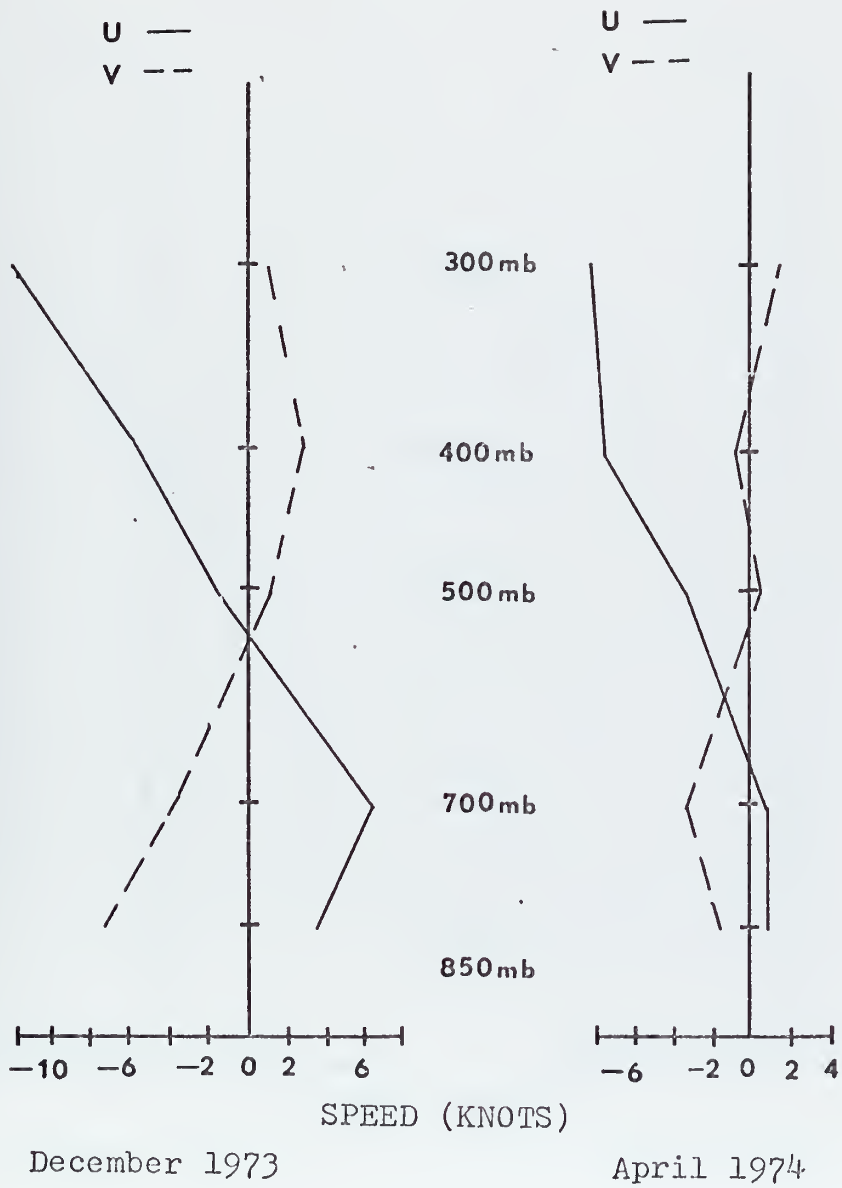
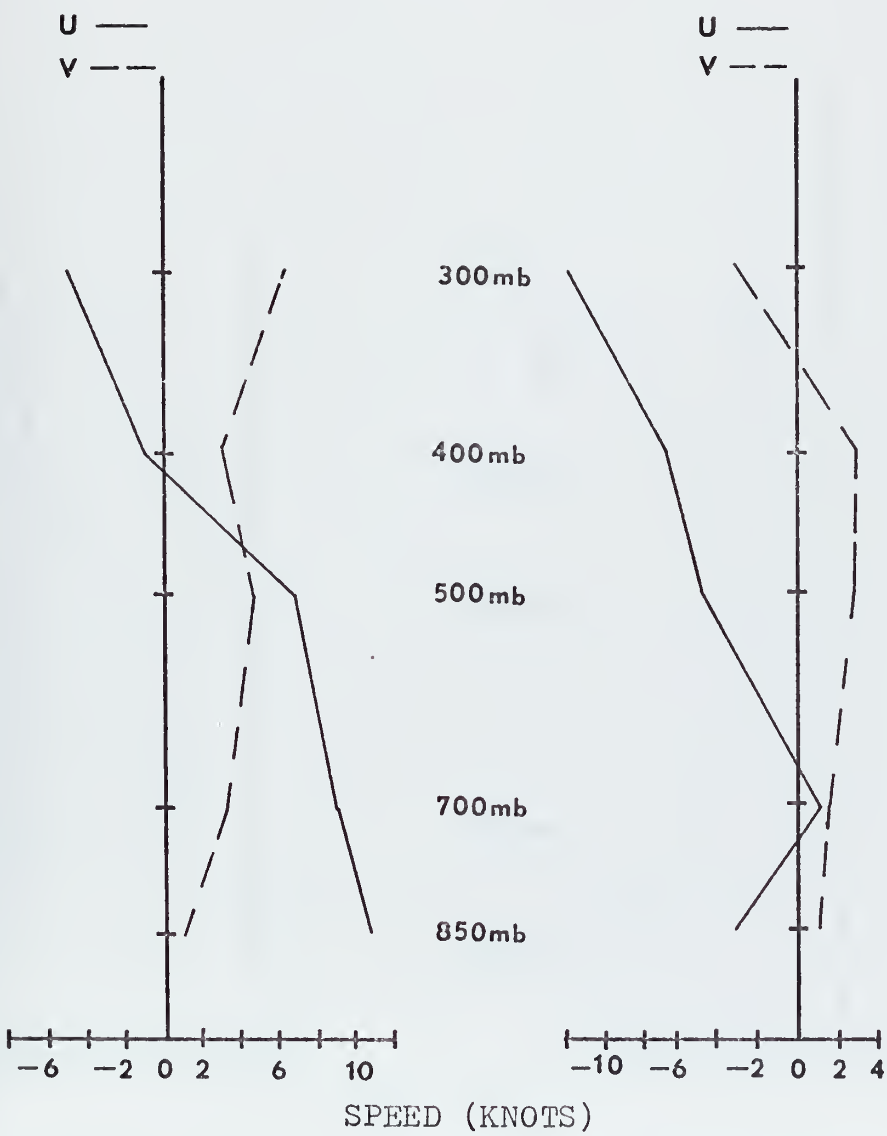
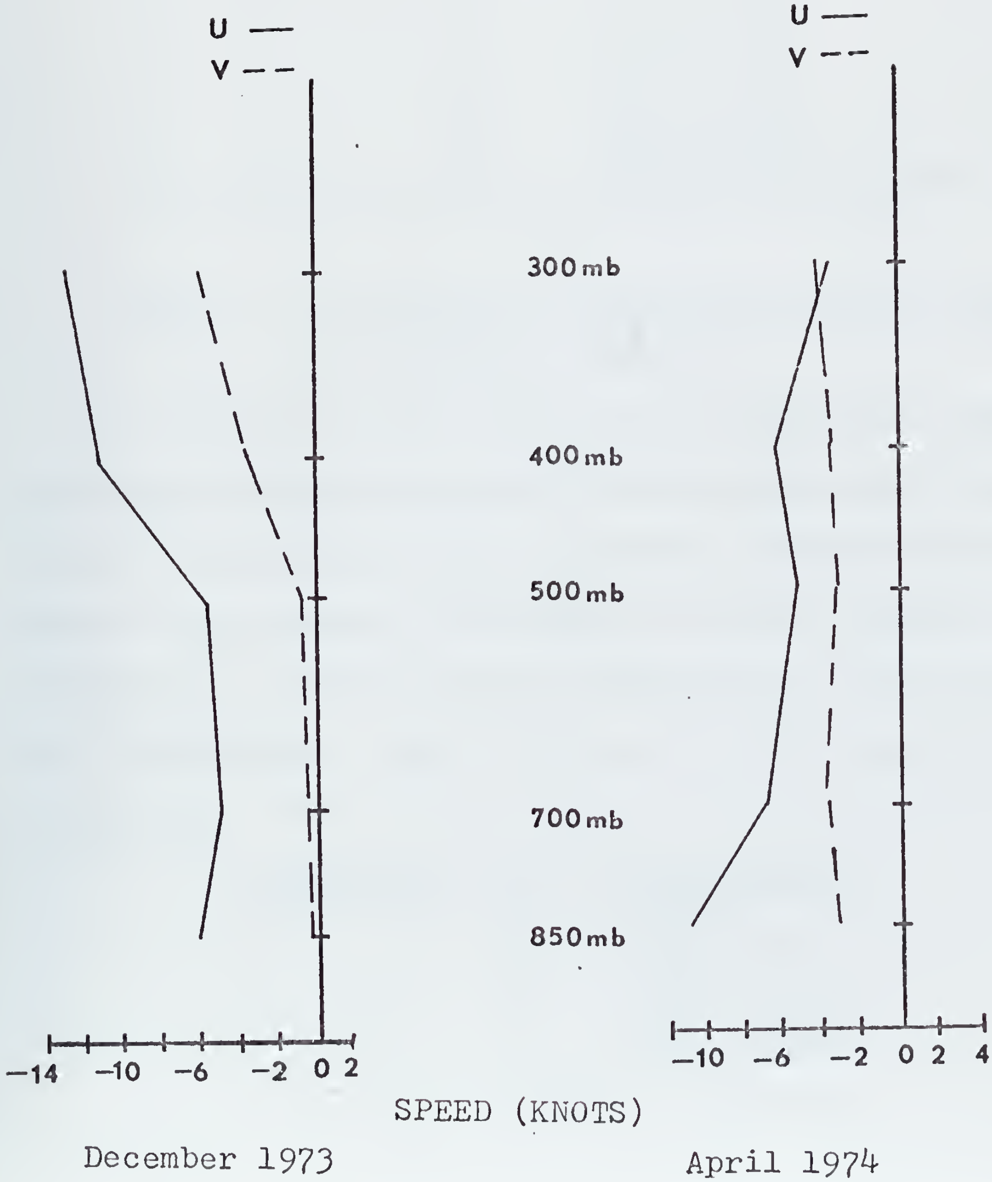


Figure 11. Same as Figure 10 except for Djakarta.



December 1973 April 1974

Figure 12. Same as Figure 10 except for Cocos Island.



each station leaving a departure series. Because of the uncertainties in the data due to the interpolations and partly for the convenience of plotting, the departure winds are categorized in nine categories as shown in Table I.

CATEGORY	SPEED (KNOTS)
0	MEAN
1	0.01-2.00
2	2.01-4.00
3	4.01-6.00
4	6.01-8.00
5	8.01-10.00
6	10.01-15.00
7	15.01-20.00
8	Greater than 20.00

Table I. Categories of wind perturbations used in composite analysis.

An attempt was also made to investigate any possible relationship between the wind fluctuations and convective clouds. Cloud amount was determined subjectively from NOAA-2 visual images and NIMBUS-5 infrared imagery and categorized by the combined brightness of the region being investigated. Table II shows the five brightness categories.

CATEGORY	BRIGHTNESS
0	Clear
1	Dark Grey
2	Medium Grey
3	Light Grey
4	Solid White

Table II. Brightness categories

B. RESULTS OF TIME CROSS-SECTION ANALYSIS

The time cross-sections at Trinvandrum are shown in Figures 13-16. The October u-component analysis (Figure 13) shows an average periodicity of approximately 13 days, which agrees with the spectral findings. The fluctuations seem to appear at the upper levels first and spread downward in time.

Figure 14 shows the October v-component cross-sections. The time scale of the fluctuations appear to be more complicated and the vertical structure is not well defined. The appearance of the shorter periodicities may be indicative of the seven-day spectral peak.

At first look, the April u-component time cross-section (Figure 15) shows no obvious periodicity. However, if extrapolation in time is considered, a somewhat longer period on the order of 20 days may be assumed. This long periodicity may be partly due to the linear interpolation of missing data. In this analysis, the fluctuations seem to appear at the lower levels first and then spread upward with time.

The April v-component cross-section (Figure 16) again shows no clear periodicity, only that the time scales seem to be shorter than that for u. The vertical structure of the fluctuations shows little organization.

Figures 17-20 show the time cross-sections at Minicoy. The October u-component analysis (Figure 17) appears to be fairly well organized and shows an apparent periodicity of

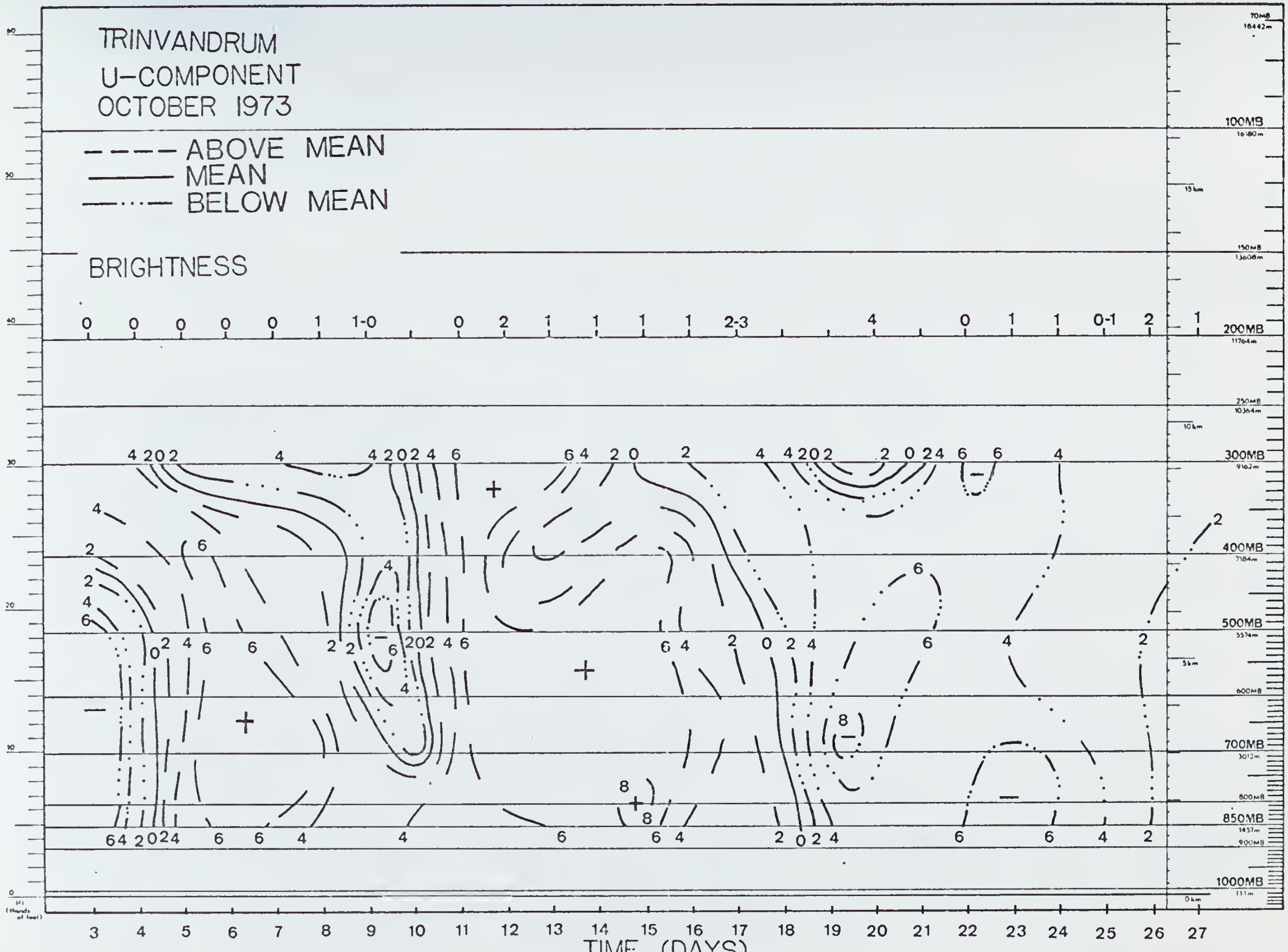


Figure 13. Time cross-section analysis of October 1973 u component perturbations at Trinvandrum.

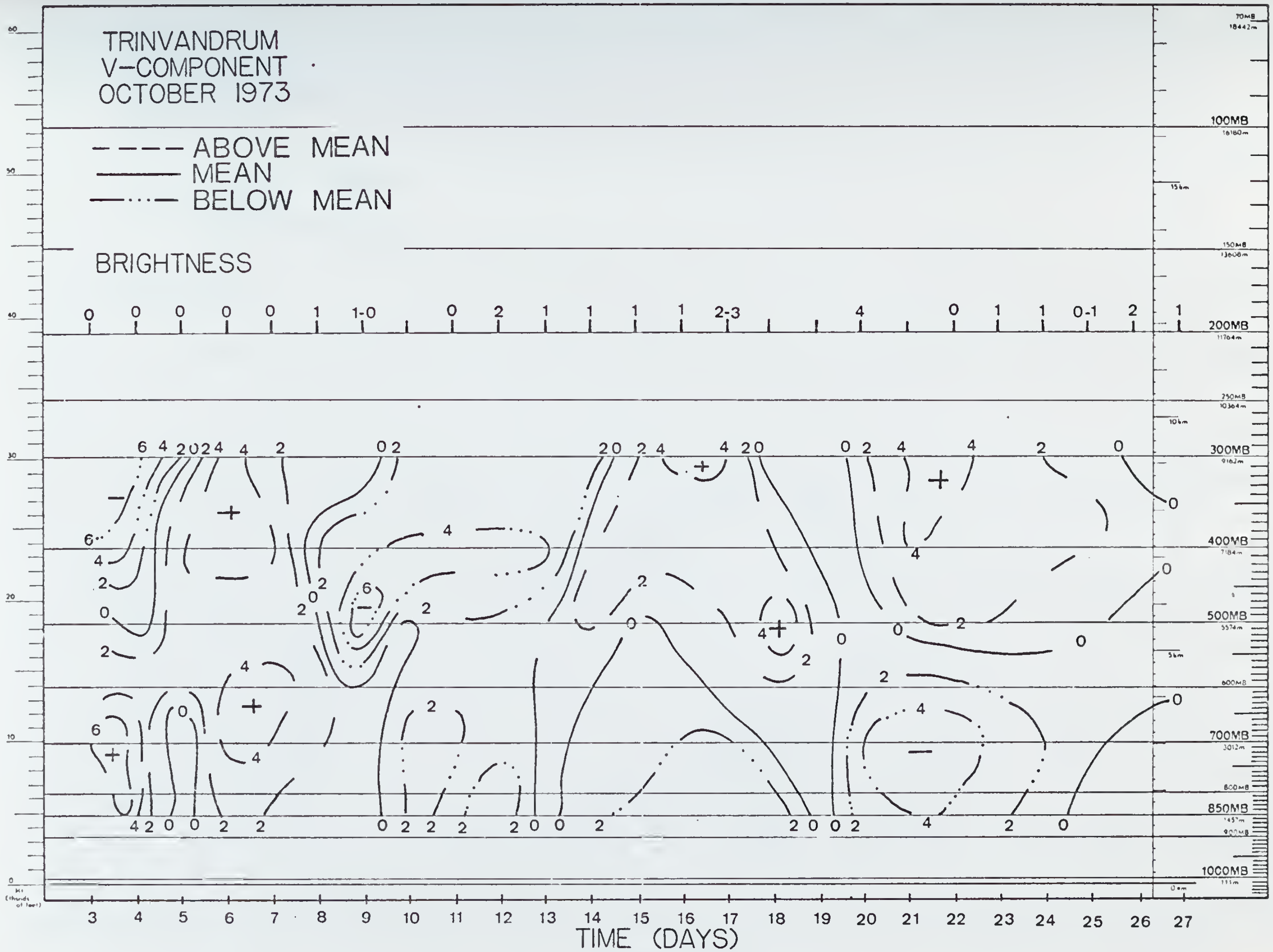


Figure 14. Same as Figure 13, except for v component.

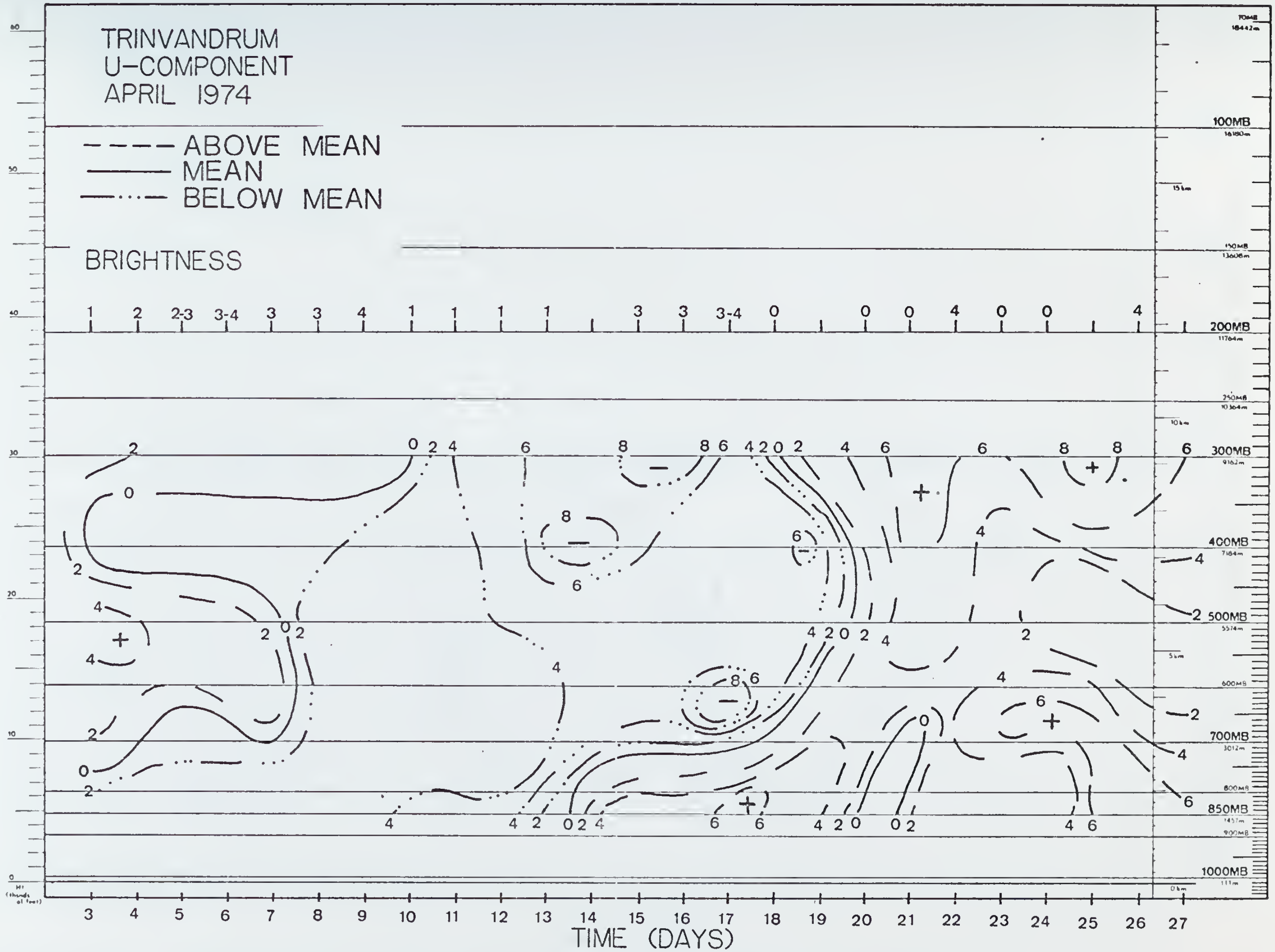


Figure 15. Same as Figure 13 for April 1974 except for u component.

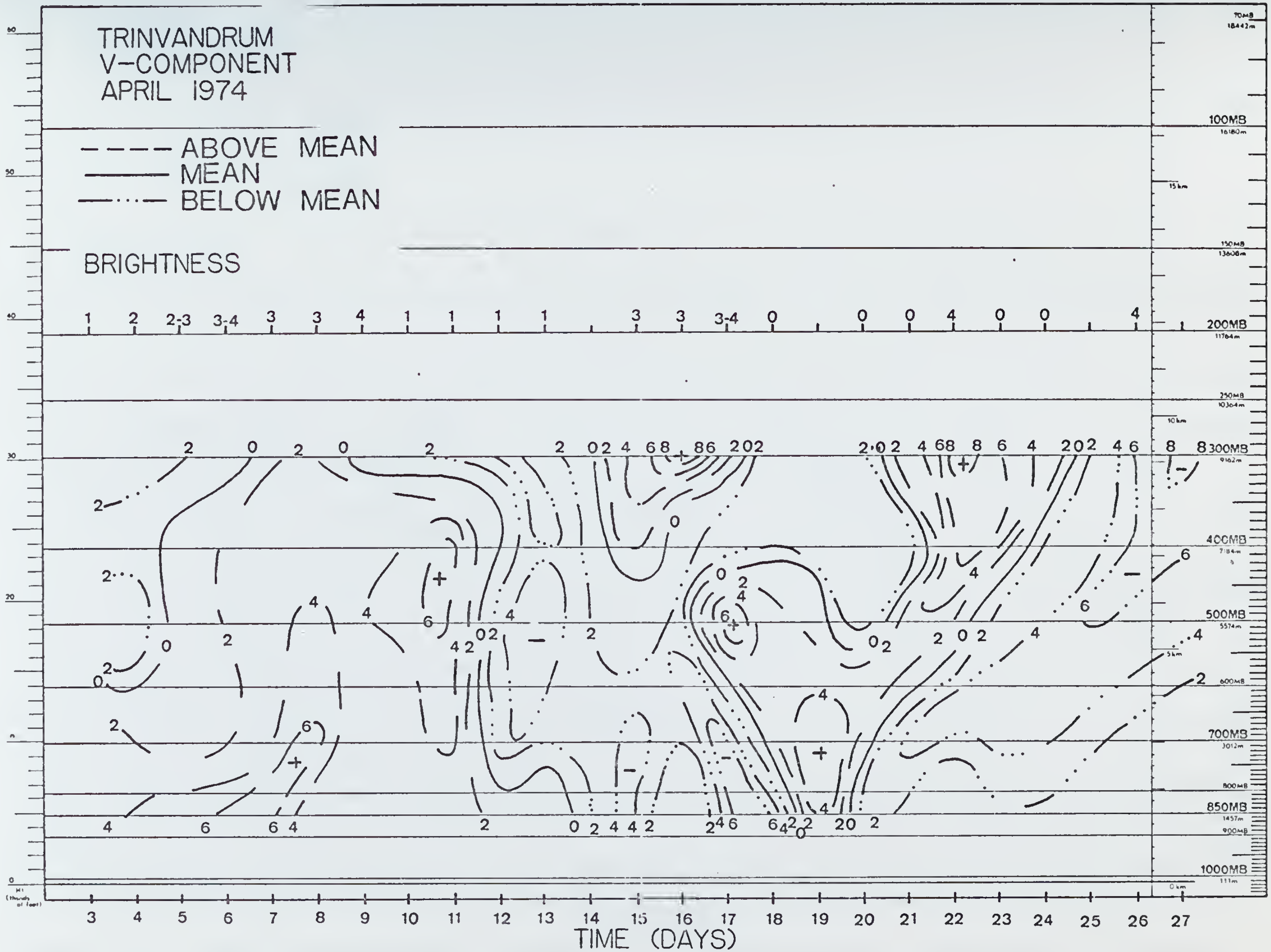


Figure 16. Same as Figure 13 except for April 1974 u component.

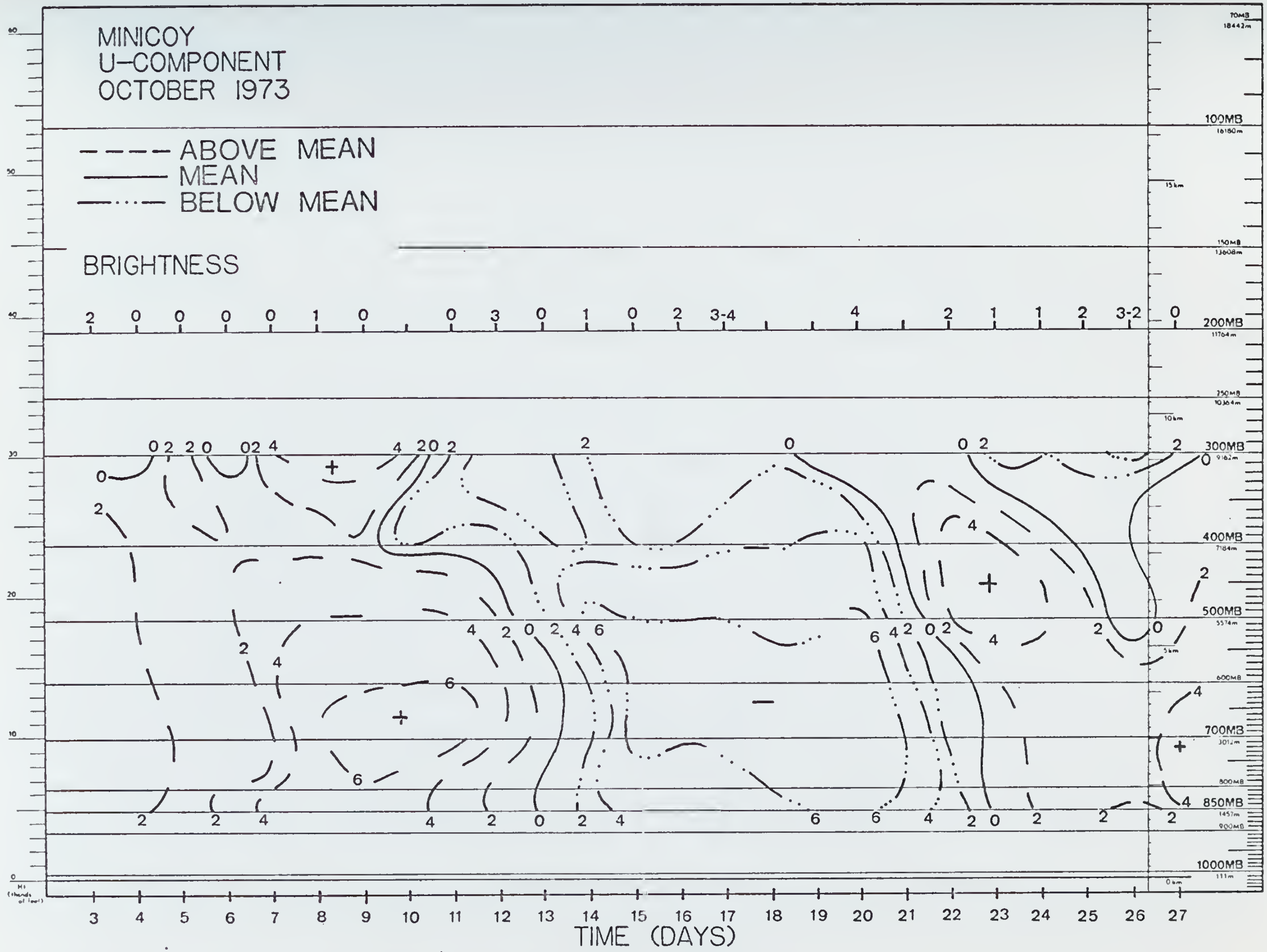


Figure 17. Time cross-section analysis of October 1974 u component at Minicoy.

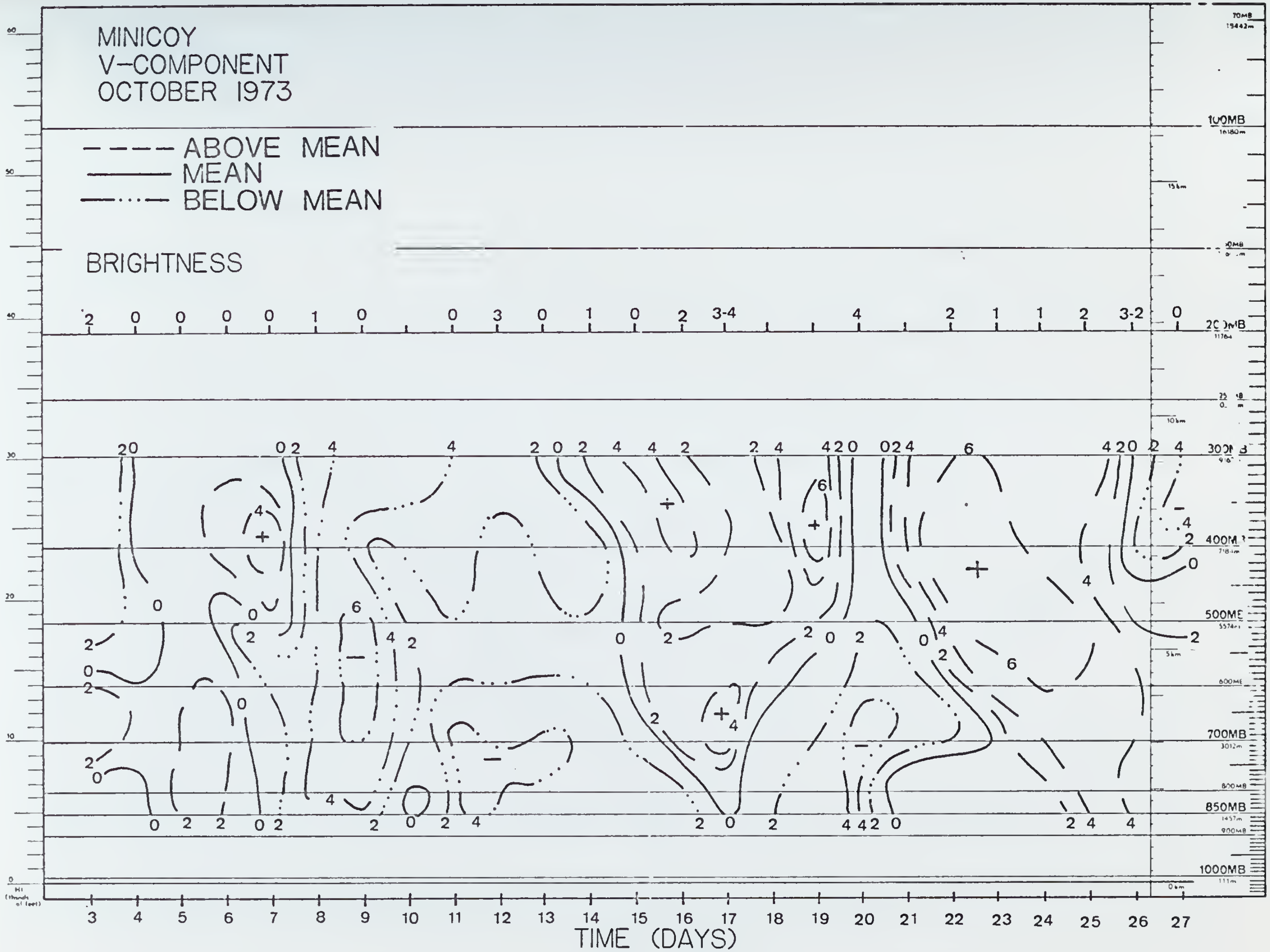


Figure 18. Same as Figure 17 except for v component.

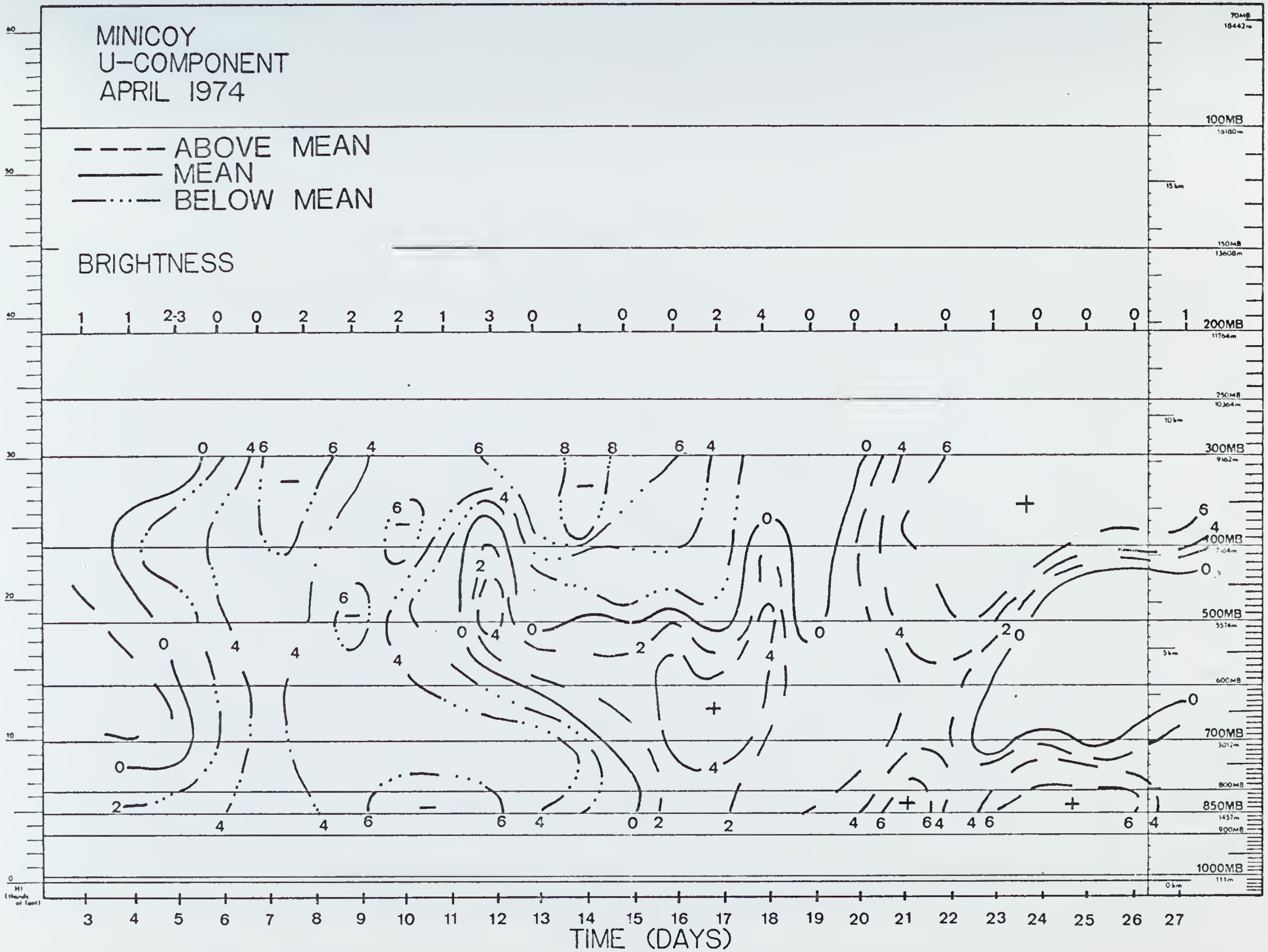


Figure 19. Same as Figure 17 except for April 1974 u component.

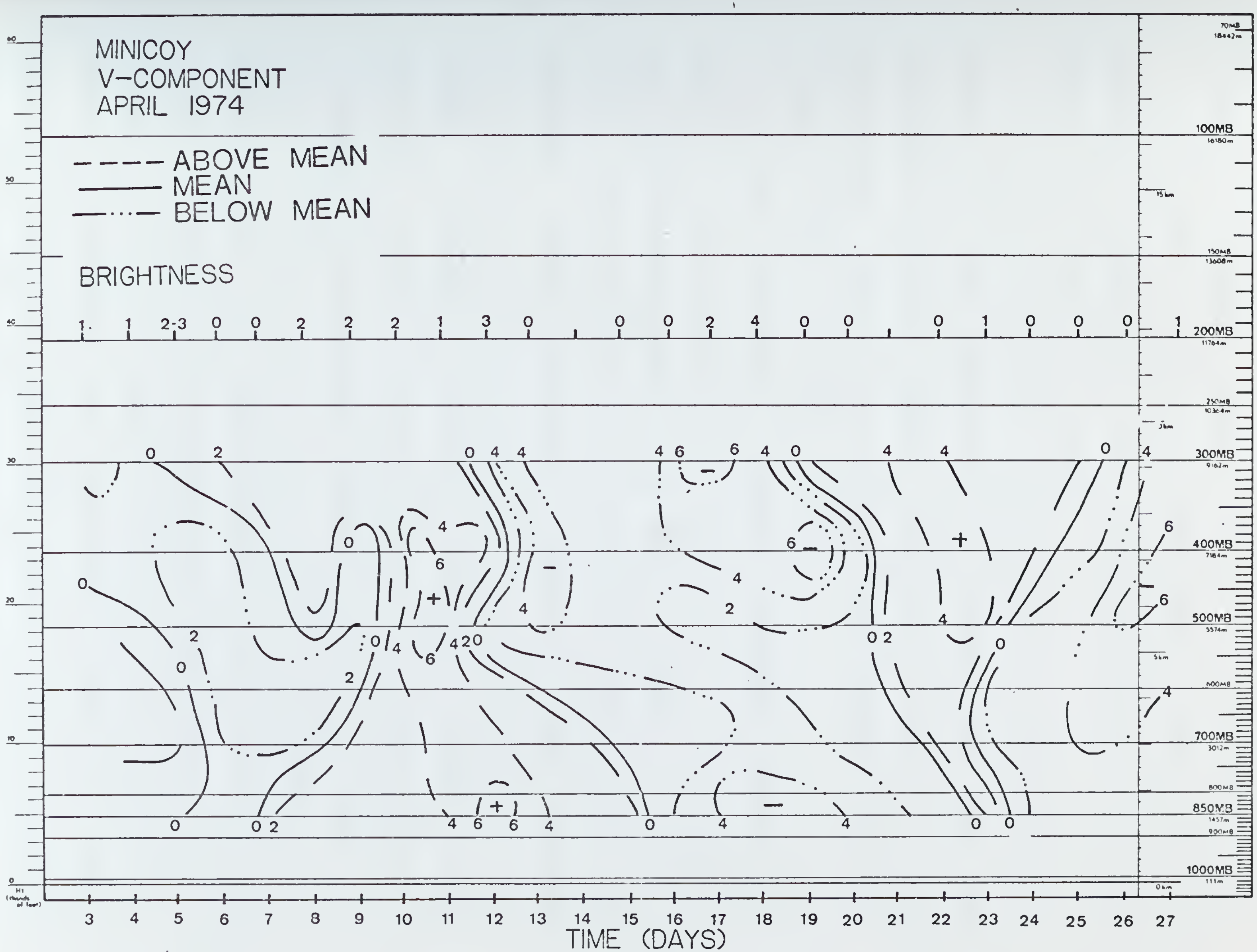


Figure 20. Same as Figure 17 except for April 1974 v component.

about 20 days, which again may be due to interpolation. The fluctuations appear at the upper levels first and seem to spread downward in time.

The October v-component cross-section (Figure 18) is generally disorganized with shorter time scales. No well-defined periodicity is obvious.

The April u-component (Figure 19) and v-component (Figure 20) time cross-sections at Minicoy show very little organized activity. Neither cross-section shows an obvious periodicity. There is no well-defined vertical structure clearly visible in either series.

At Gan, the October u-component analysis (Figure 21) shows no clear periodicity. Near the end of the month, the fluctuations appear to propagate downward in time. In the first few days, high frequencies dominate the fluctuations. If one goes back to Figure 13, which shows the u fluctuation at Trinvandrum, similar feature can be detected. Tracking the negative (easterly) u departure for day eight at Gan to day nine-ten at Trinvandrum appears to suggest a northeastern movement of this particular system. However, this feature cannot be detected at Minicoy (Figure 17), which is west of Trinvandrum and north of Gan, because of the missing data during these days. The October v-component analysis (Figure 22) also shows no obvious periodicity. The fluctuations appear to be more organized vertically than those found in the u component. They also show slight downward propagation in time.

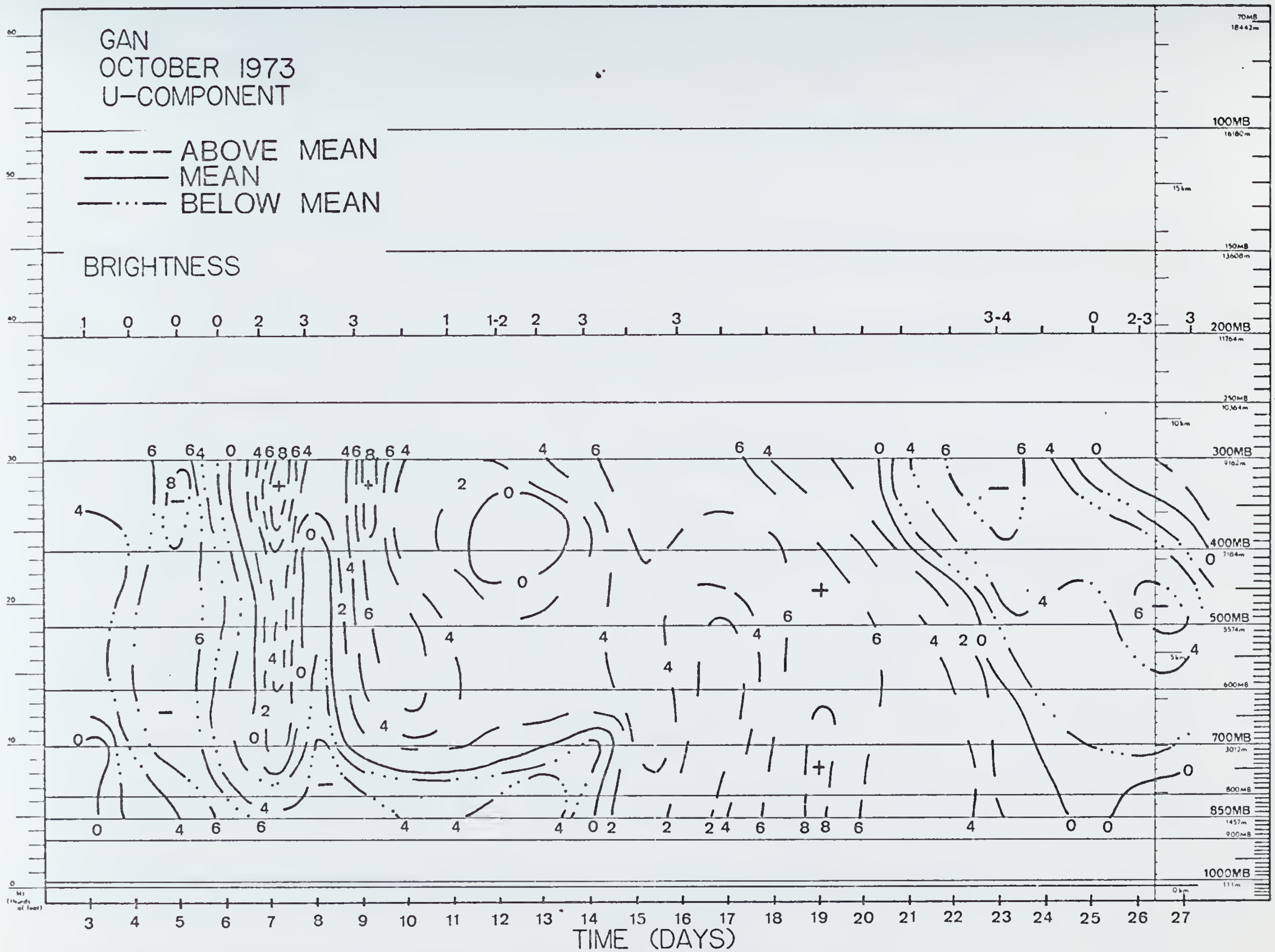


Figure 21. Time cross-section analysis of October 1973 u component at Gan.

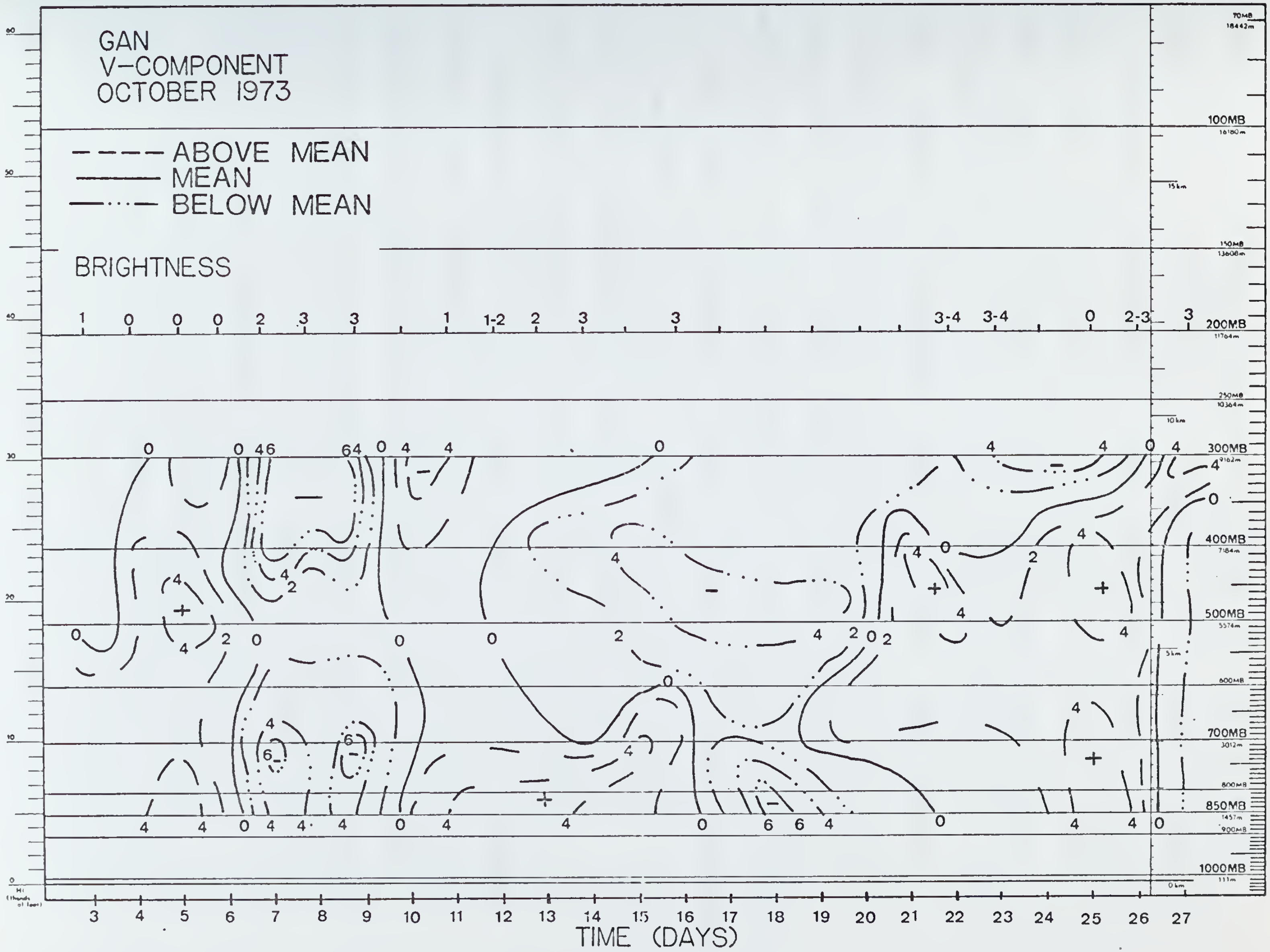


Figure 22. Same as Figure 21 except for v component.

The April u-component and v-component cross-sections (Figures 23 and 24) show hardly any organization at all, except that downward propagation (from 400 mb) is again apparent for the negative u anomaly in the last few days.

Figures 25-28 show the time cross-sections at Singapore. The fluctuations in the December u-component analysis (Figure 25) appear to have an average periodicity of approximately 10 days. The vertical structure, in this case, appears to propagate upward in time. The December v-component (Figure 26) analysis shows about 3.5 waves at the lower levels, which indicate a periodicity close to seven days. Downward propagation is apparent for this case.

The April u (Figure 27) and v (Figure 28) cross-sections at Singapore do not give a clear periodicity. Interpolation of missing data may be responsible for the apparent long period at the first half of the period.

Figures 29-32 show the time cross-sections at Djakarta. The December u-component analysis (Figure 29) shows well-organized fluctuations with just one wave for the entire 23-day period, while the April u section (Figure 31) shows two waves for the period. The v sections (Figures 30 and 32) show no well-organized fluctuations.

At Cocos Island, all time cross-section analyses (Figures 33-36) show well-organized fluctuations. The u-component analyses for both months show an average periodicity of about 12-16 days, and so does the v section in December. On the other hand, the v-component analysis

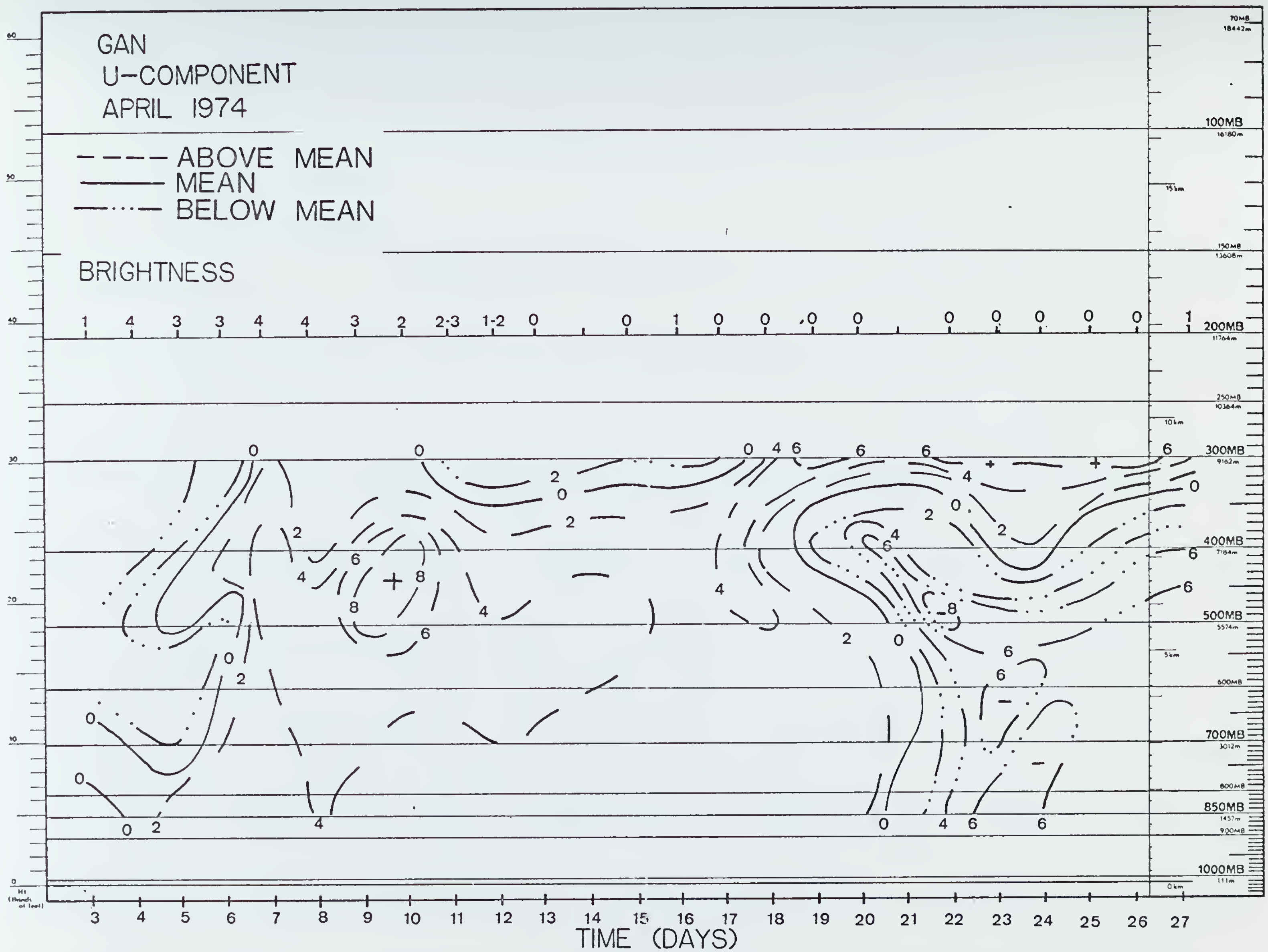


Figure 23. Same as Figure 21 except for April 1974 u component.

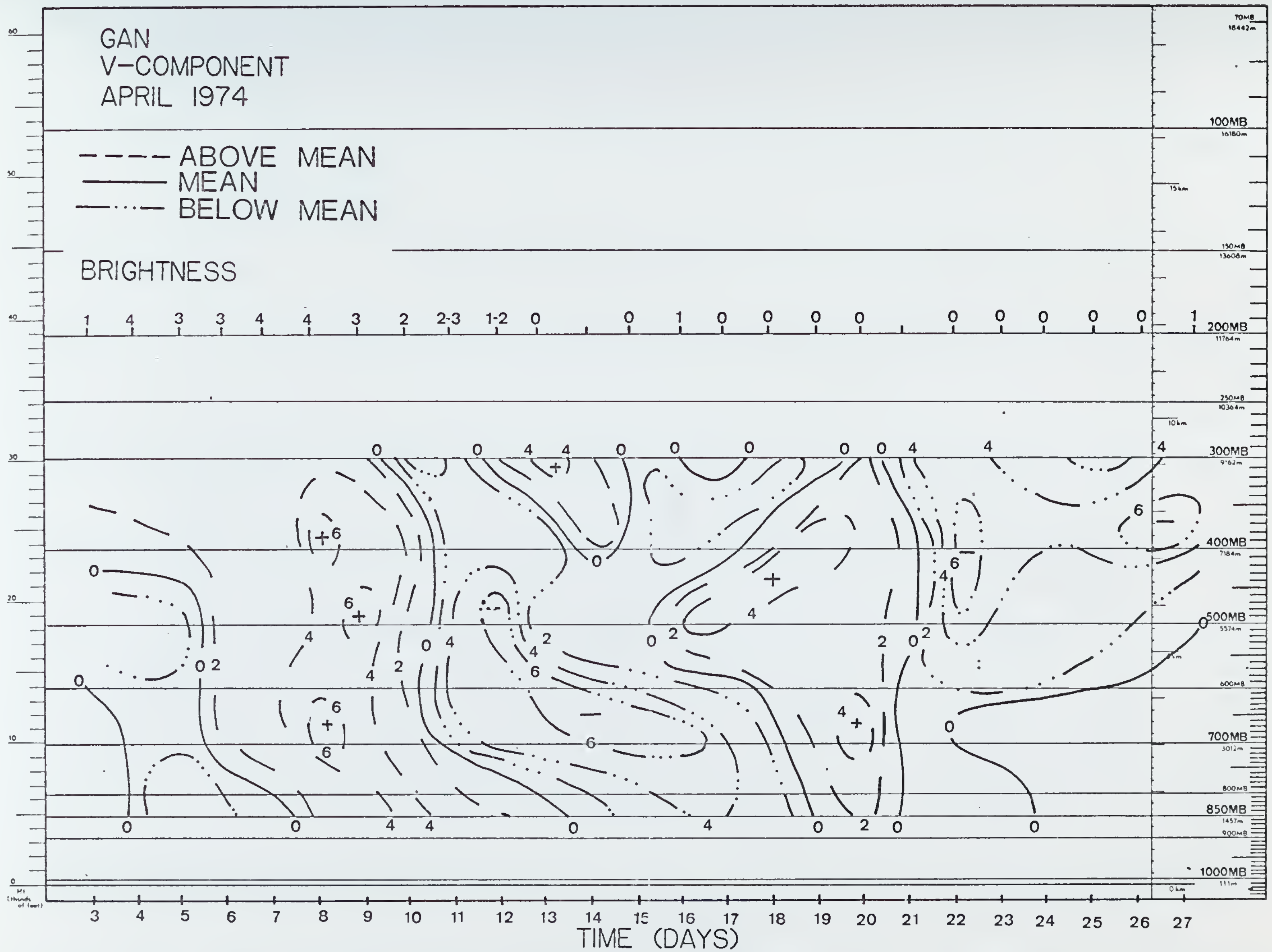


Figure 24. Same as Figure 21 except for April 1974 v component.

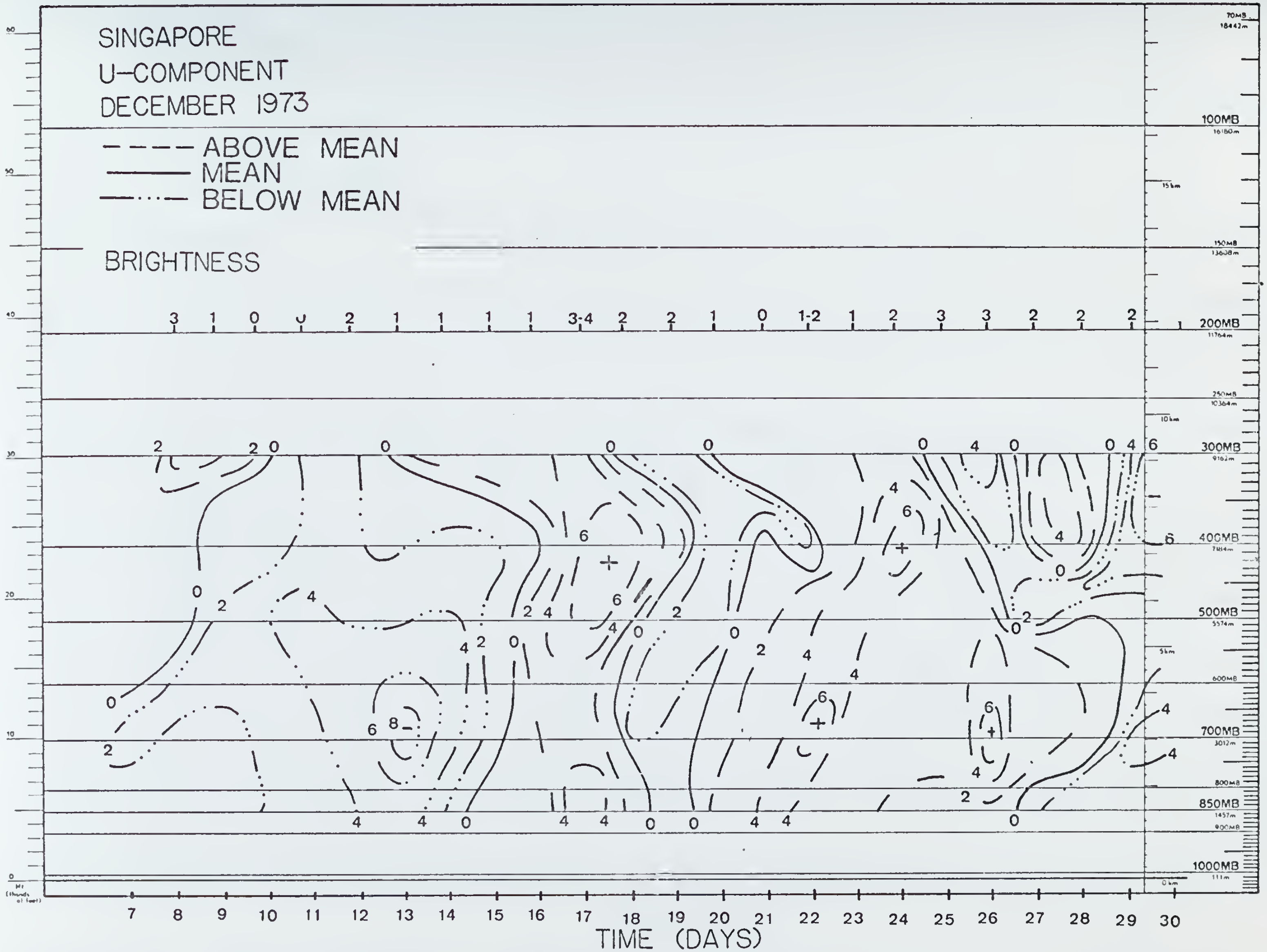


Figure 25. Time cross-section analysis of December 1973 u component at Singapore.

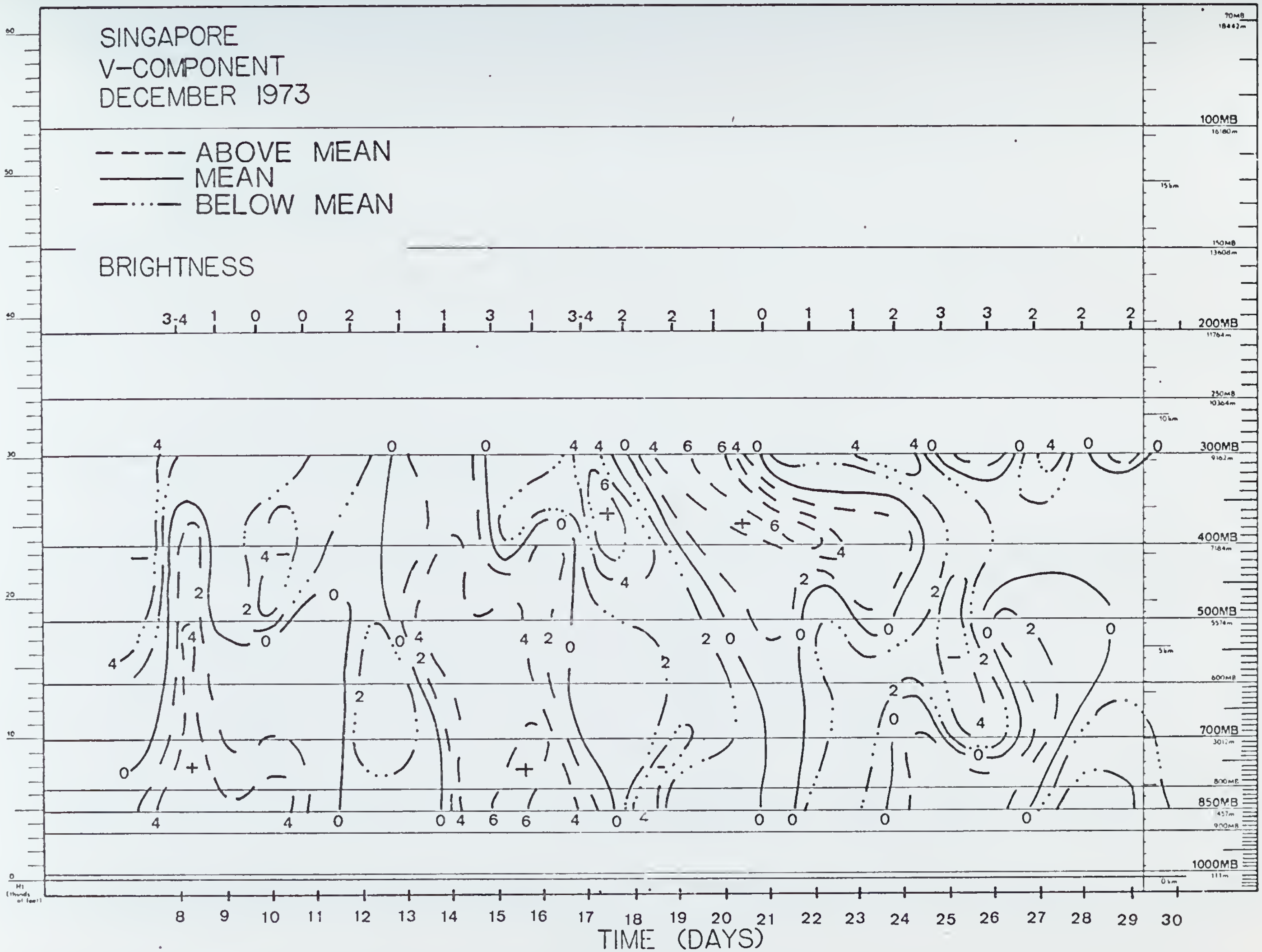


Figure 26. Same as Figure 25 except for v component.

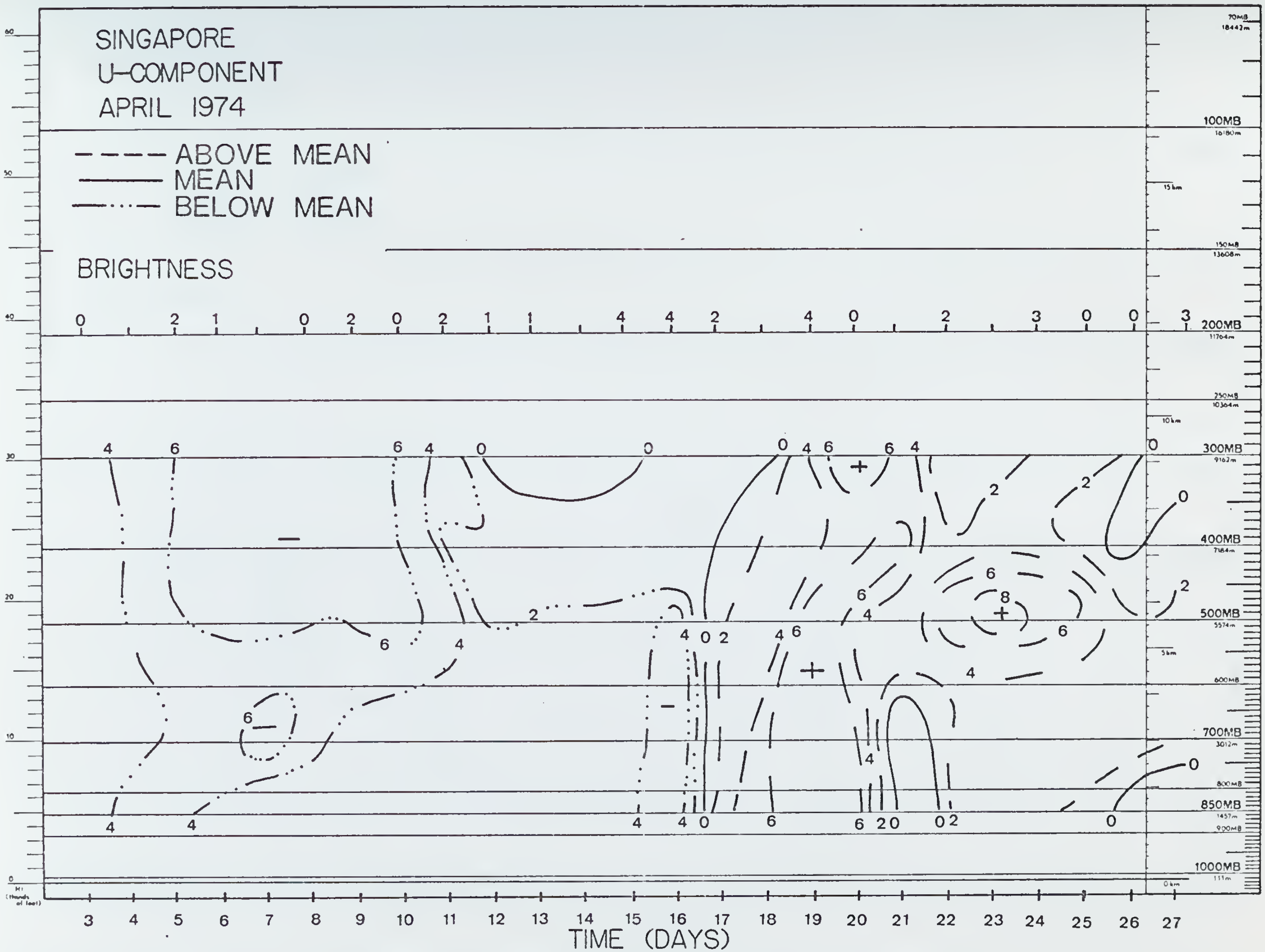


Figure 27. Same as Figure 25 except for April 1974 u component.

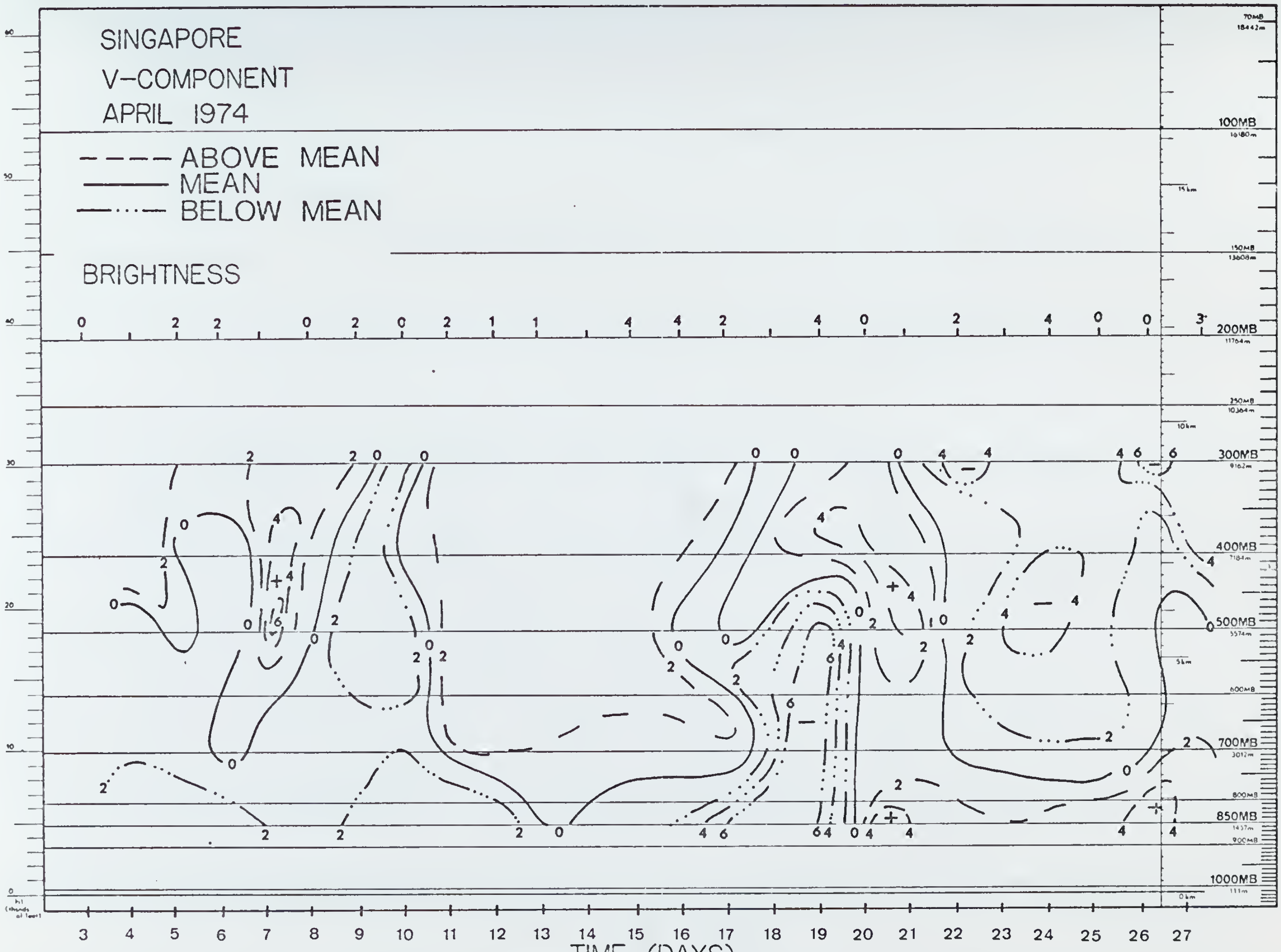


Figure 28. Same as Figure 25 except for April 1974 v component.

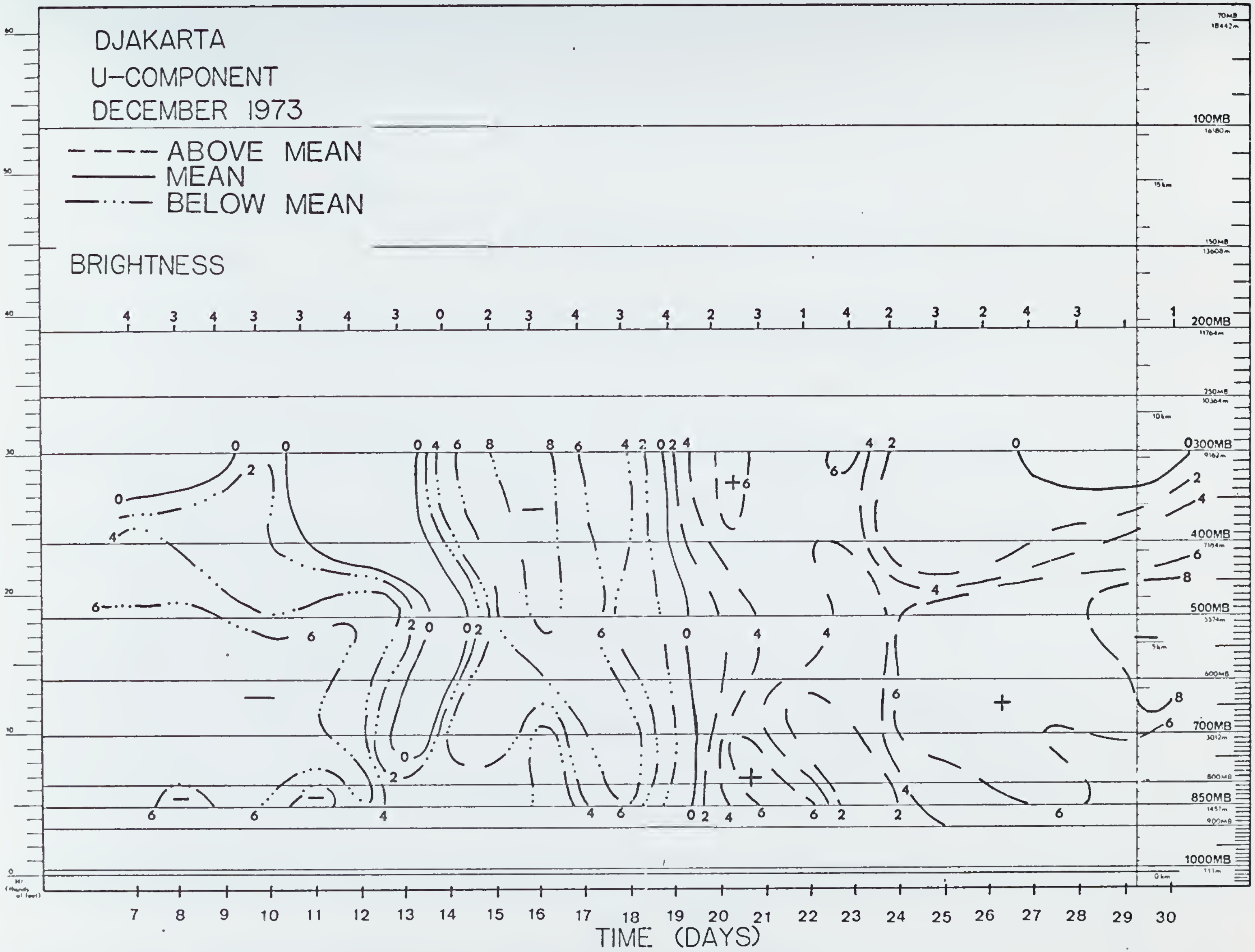


Figure 29. Time cross-section analysis of December 1973 v component at Djakarta.

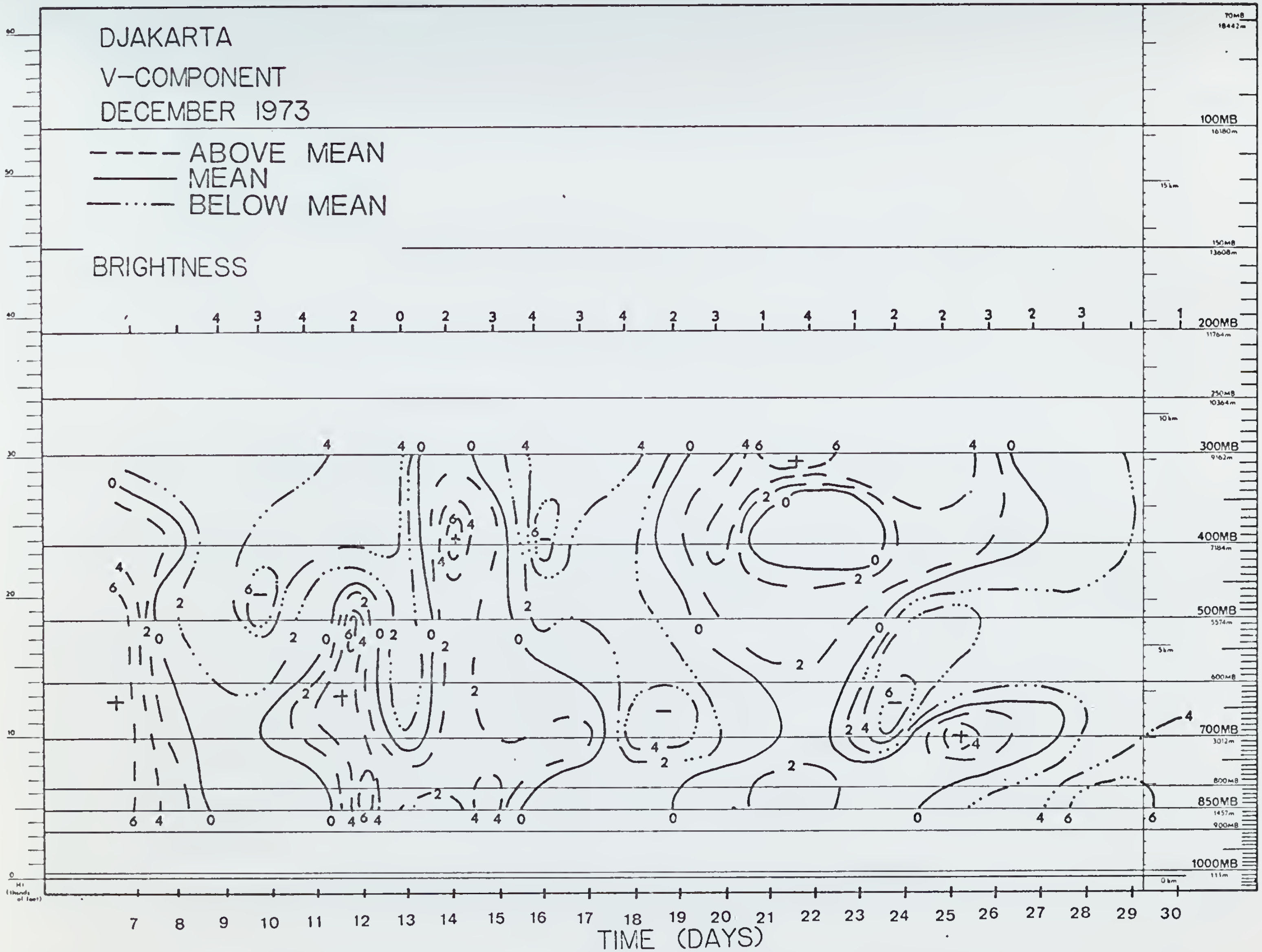


Figure 30. Same as Figure 29 except for v component.

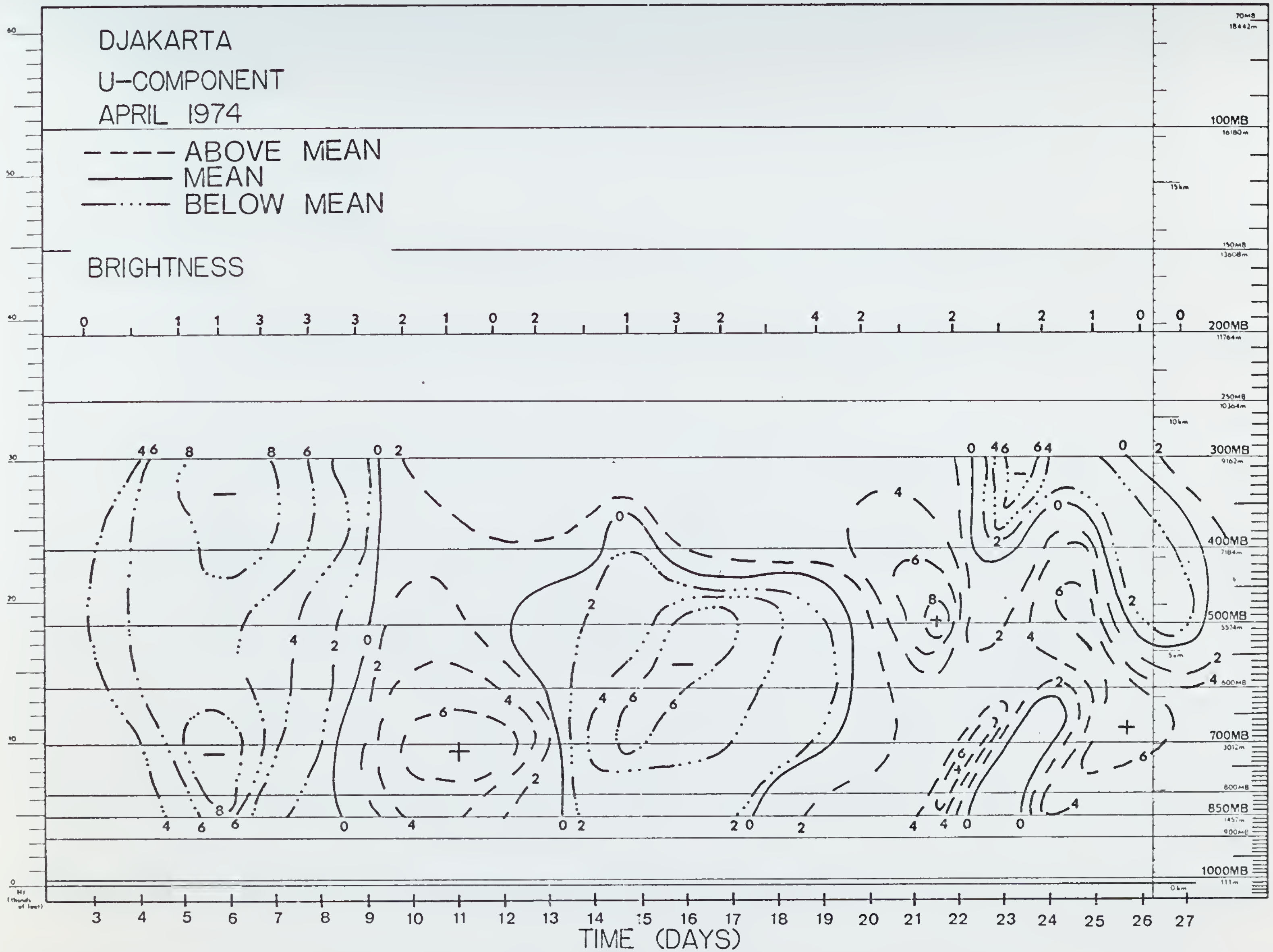


Figure 31. Same as Figure 29 except for April 1974 u component.

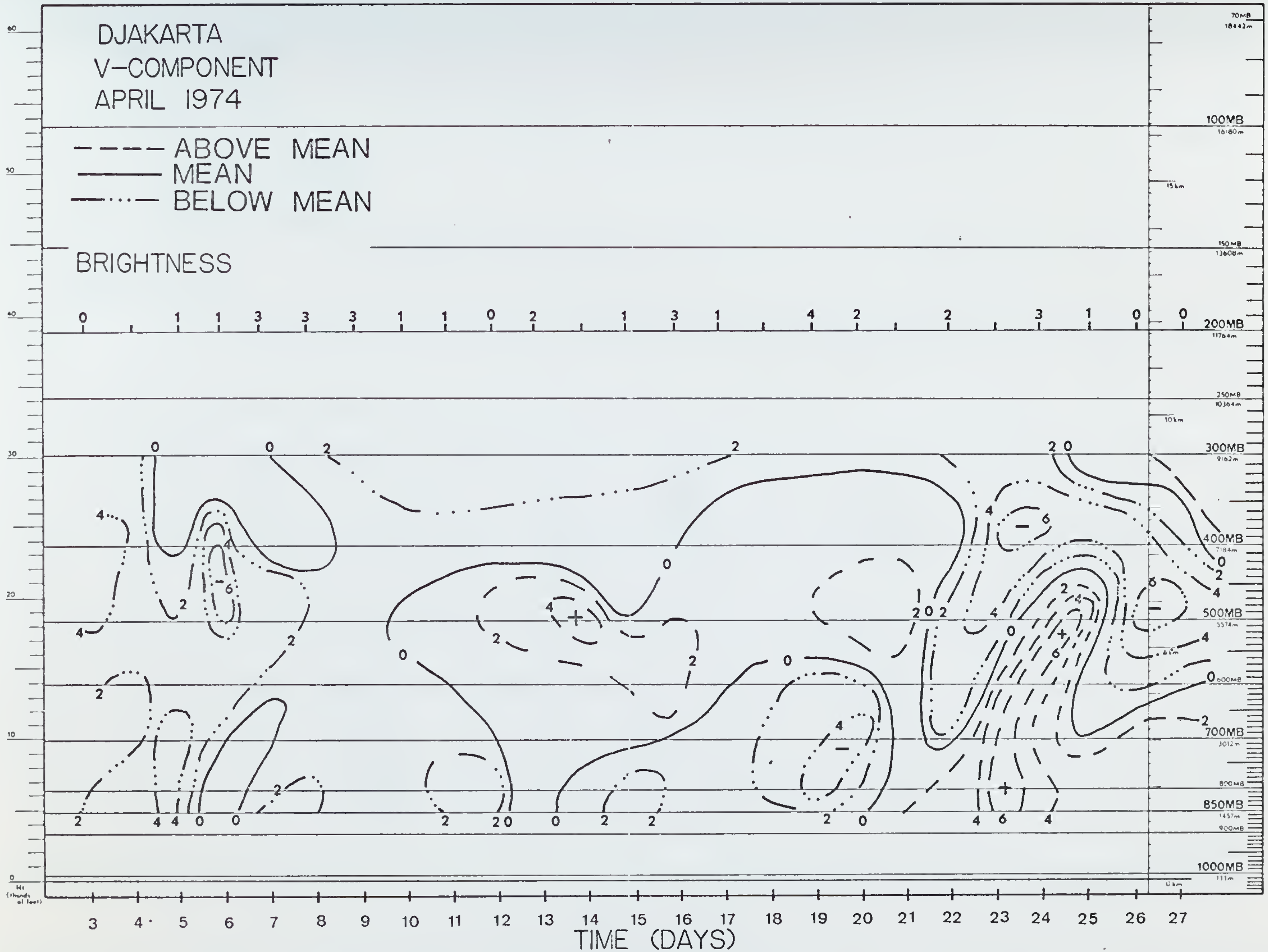


Figure 32. Same as Figure 29 except for April 1974 v component.

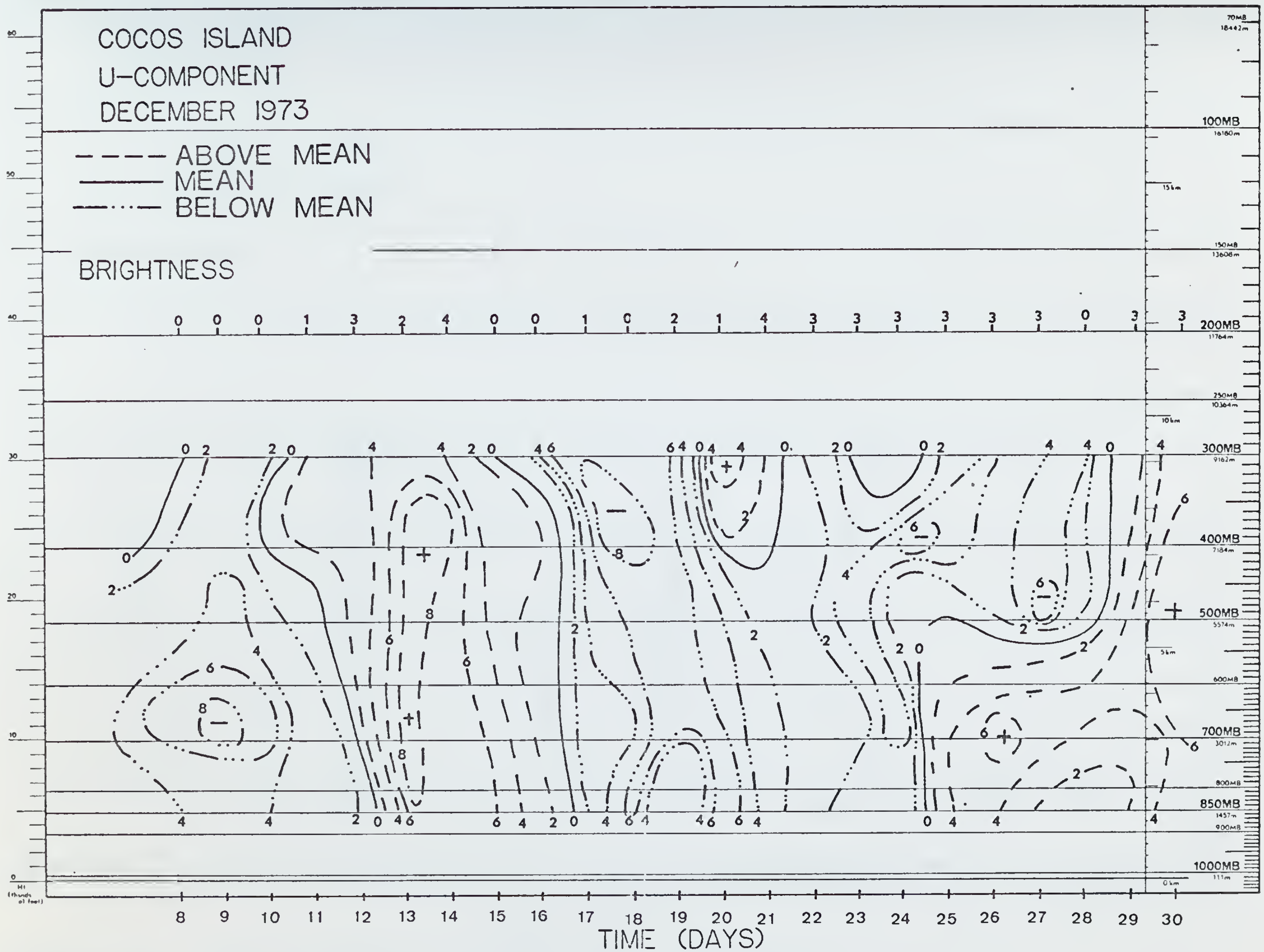


Figure 33. Time cross-section analysis of December 1973 u component at Cocos Island.

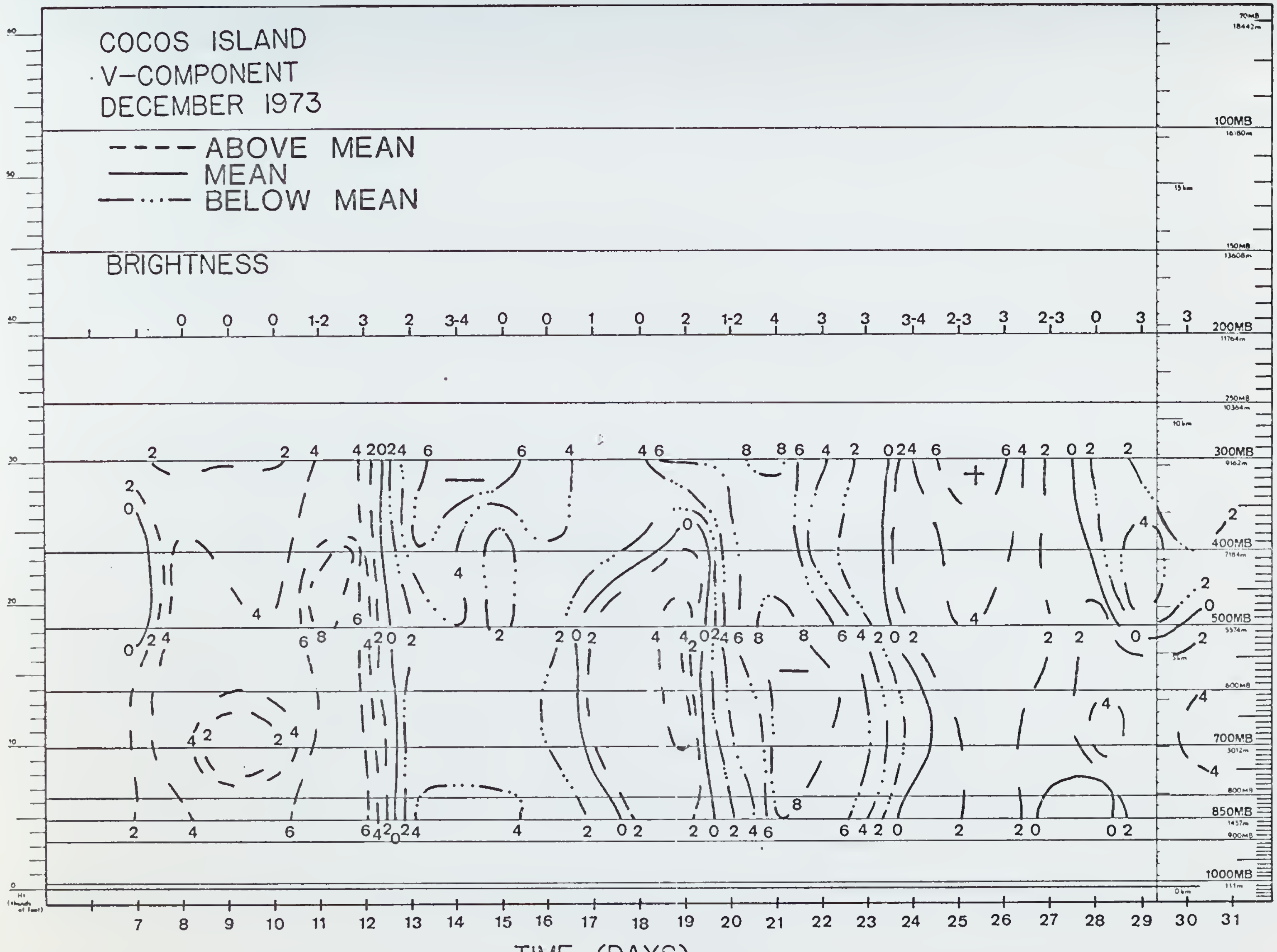


Figure 34. Same as Figure 33 except for v component.

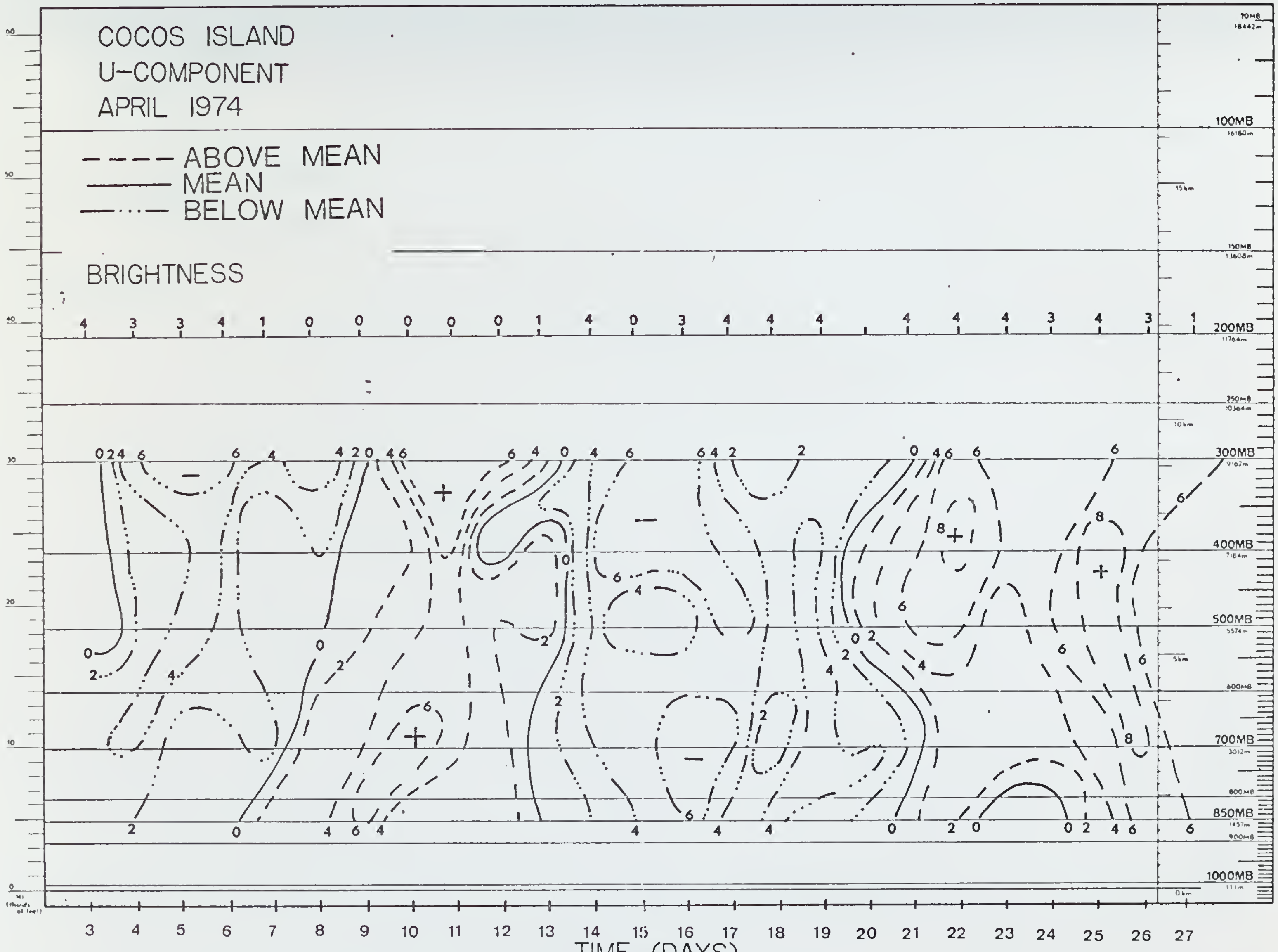


Figure 35. Same as Figure 33 except for April 1974 u component.

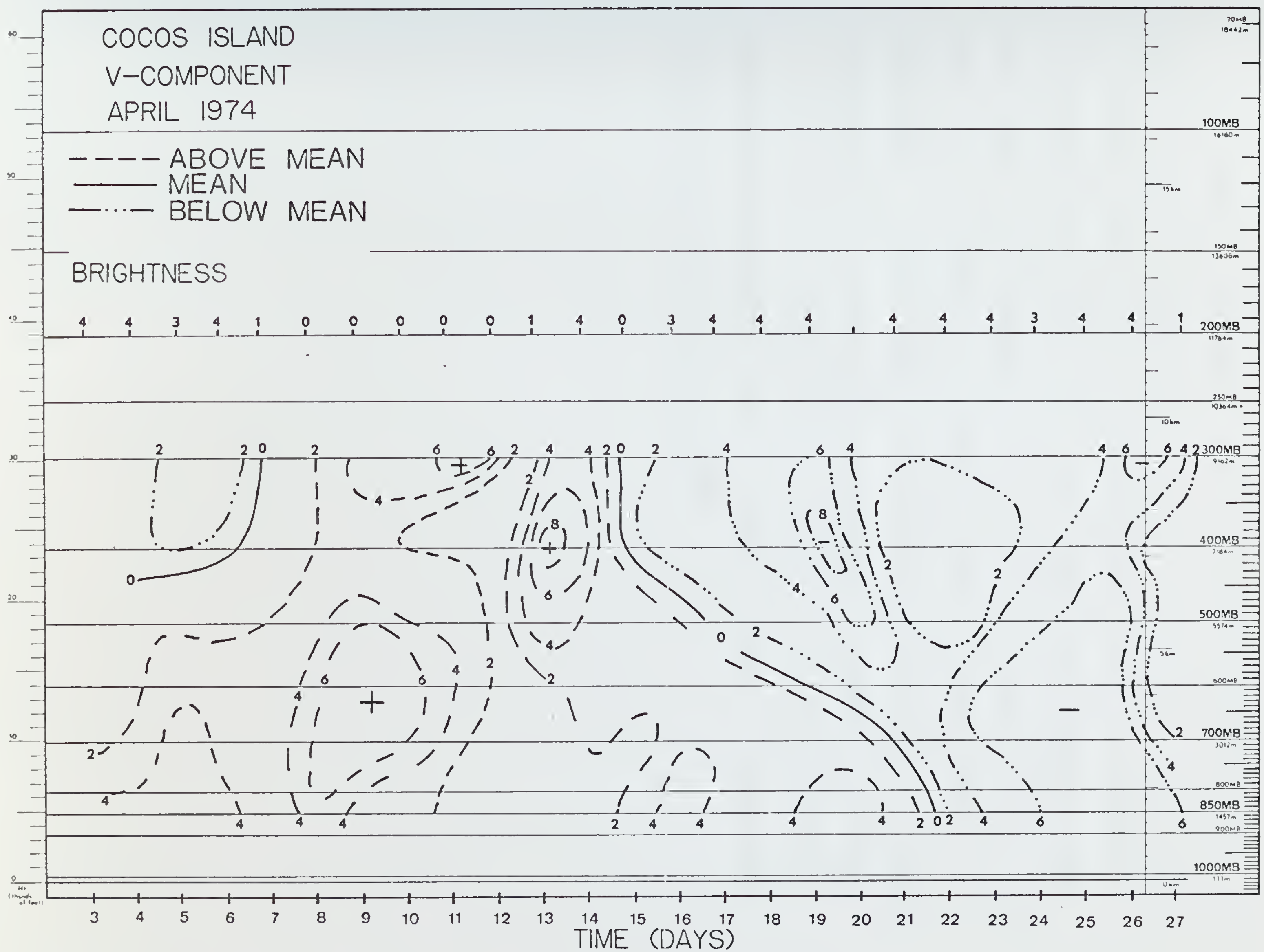


Figure 36. Same as Figure 33 except for April 1974 v component.

shows an approximate period of about 24 days. Except for the April v component, the fluctuations are nearly in phase in the vertical.

In summary, the results of the time cross-section analyses vary widely from station to station. However, in several cases, the u component did show an average periodicity of about 10-20 days, where the longer limit may be due to interpolation of missing data. On the other hand, the v component generally shows shorter scale fluctuations. In most cases, the fluctuations seem to appear at about 400 mb first and then spread downward in time.

No definite relationship between cloud brightness and wind fluctuations can be found. Thus, it seems that the two fields are not related.

V. CONCLUSIONS

The power spectra indicate a common peak of about seven days at three of the four stations analyzed. This periodicity has been observed by Malay (1974) at Guam and Subbaramayya and Rao (1974) at Trinvandrum. Other possible periodicities found were four-five days at two stations (Gan and Cocos Island) and thirteen days at one station (Trinvandrum). A period of fifteen-sixteen days has been observed in precipitation data over the west coast of India (Murakami 1972), which may be related to the thirteen-day peak at Trinvandrum found in this study. The variation of spectral characteristics between stations and levels plus the lack of significant coherence values cast considerable doubts to the significance of the spectral peaks.

Time cross-section analysis for two one-month periods also provides little solid information. It was found, however, that the u component seems to have a longer time scale of fluctuation than the v component. This is consistent with observational findings elsewhere, which may be a general characteristic of tropical oceanic disturbances. In addition, the fluctuations in most cases appear to begin at upper levels and then propagate downward at a fairly fast rate.

Due to the general poor quality of the data and the low density of available reporting stations, very limited

results have been found from this study. Further study is suggested, but only after the quality of the data can be improved.

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